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2019 was proclaimed the "International Year of the Periodic Table of Chemical Elements (IYPT2019)" by the United Nations General Assembly and United Nations Educational, Scientific and Cultural Organization (UNESCO) (1). Johnson Matthey celebrated this significant milestone by looking at the ways in which the company has used the periodic table to understand the inter-relationships of elements, help promote sustainable development and solve some of the world’s biggest challenges (2–4).

The Johnson Matthey Technology Review included a whole year of special themed issues devoted to using resources more efficiently: encapsulating active ingredients to make more from less; the need for accurate sensors to enable new technologies; efficiency gains from continuous manufacturing replacing batch style processes; and efficient materials design for the energy applications of the future.

Elements for Life

Certain elements such as the platinum group metals (pgms) have unique qualities with which regular readers of this journal will be familiar. The top ten downloaded articles from the Johnson Matthey Technology Review and Platinum Metals Review archives over the past 12 months reflect these qualities and their relevance to solving the challenges faced in industrial science and technology today.

The elements featured, which include the pgms, lithium and nitrogen among others, are indispensable for applications in catalysis and the control of harmful emissions. They have enabled

Top Ten Downloaded Articles from Archives July 2018–July 2019

advances in medical treatments, human nutrition, improved energy devices and other improvements to human life. Furthermore, there has long been interest in using precious metals as efficiently as possible, from their extraction to their use and end-of-life recycling. These principles of sustainable resource use connect with the theme of this issue: the circular economy.

**Circular Economy: A Way Forward?**

The circular economy is a conceptual framework that aims to rethink sustainability by designing from first principles. In recent years the number of publications on this topic has vastly increased as discussed in this issue (5). The principles of circular economy are wide ranging and there is no single agreed definition, but discussions tend to include design for circularity, resource reduction, reuse or recycling, rethinking materials and renewable energy (5). Misconceptions and barriers are discussed (6) along with the potential of new technologies to facilitate new ways of thinking about sustainability (5, 7). Many studies link the idea of circularity to biological cycles and design innovation for both products and processes is a thriving area of research (8, 9).

Recycling of both precious and base metals has of course long been established. Recycling plays an important part in replacing linearity with circularity that goes beyond metals. The recent attention being given to plastics, with their damaging environmental consequences, has led to projects investigating the feasibility of recycling these ubiquitous materials (10). The principles of circular economy can be applied across many industries: from consumer goods to the petrochemicals, automotive and pharmaceutical industries.

The possibilities offered by new technologies to enable sustainable practices, and the impact of circular economy thinking on innovation, represent exciting opportunities to enhance human life, challenge preconceptions and use science to solve the recurring problems of our times. We hope you will enjoy reading the thought-provoking articles in this issue.

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**References**

Closed-Loop Recycling of Polymers Using Solvents

Remaking plastics for a circular economy

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Recycling of plastic is an established technology contributing to a circular economy. A sustainable society requires recycling to produce high quality feedstocks from all types of reusable waste. New recycling technologies will help to improve waste management practices, for instance dissolving plastic waste in a solvent to purify and maintain its material properties. In solution it is also possible to depolymerise polymers into monomers that can be used to remake virgin-grade material. In this review the advantages and disadvantages of three solvent-based recycling processes will be considered: separation of cotton and polyester (polyethylene terephthalate (PET)) textiles, chemical recycling of polylactic acid (PLA) and dissolution-precipitation of polyvinylchloride (PVC). The current state of the art and future prospects are discussed, including a brief overview of how solvents are being used to process other types of plastic waste.

Introduction

There is an obvious and increasing need to preserve valuable resources and reduce waste and pollution. Maximising the functional lifetime of materials with reuse and recycling practices has long-term benefits (1). These themes are embodied in the circular economy concept, where materials are considered in terms of the service they provide when fabricated into products (2). Extended product lifespans deliver more service from a material, while waste represents lost potential.

The EU and China are the two regions with the most prominent circular economy strategies. Specific policies have been established since 2015 in the EU (2) and even earlier by the Chinese government (3). Although the regulatory measures are broad, encompassing critical materials and product (eco)-design, European law focuses on recycling targets. China has additional policies encouraging industrial symbiosis so responsibility for waste is shared, including heat and material (waste) outputs of one industry being provided as the input for another. Academic interest in the circular economy concept is high, ranging from policy to product design to improved recycling technologies.

Although recycling targets are an obvious, easily monitored and (potentially) enforceable legislative measure to promote a circular economy, there are many end of life options that preserve a much greater degree of product functionality. Waste avoidance is not enough, if it were then current trends towards biodegradable packaging, waste incineration and landfill reduction would be sufficient. Maintaining and extending the maximum value of limited resources is necessary for a sustainable society. In order to reuse, repair, remanufacture and refurbish products, manufacturers need to be involved in the value chain beyond production. This could be in formal partnerships with waste processing agencies or by implementing extended producer responsibility, pledging to return defunct products to use (4, 5). A change of emphasis towards valuing a product’s service not its material worth prompts a
reduction in waste and better use of resources. For example, chemical leasing is a business model where payment for a service is based on productivity, not how much material changes hands (6). Under this business model it is possible to buy paint on the basis of what surface area is to be coated or industrial solvents according to how much apparatus needs to be cleaned or degreased. It is now important to the selling party to provide as little product as possible to maximise profit and in doing so minimise waste. Similar principles are being applied to consumer purchases of clothes and electronic devices on a leasing basis, rather than buying an article outright and eventually disposing of it (7).

Inevitably all products will become obsolete and the obvious way to extend the value provided by finite materials at this point is through recycling. Recycling processes for most types of material produce an inferior product that enters lower value applications, known as open-loop recycling or downcycling. Coupled with poor collection rates, this means 95% of the economic value of the plastic market is lost after a single use (8). Mechanical recycling is effective for PET, polyethylene (PE) and polypropylene (PP), whereby the waste is shredded, melted and remoulded (9). Recycling infrastructure for other polymers is more limited internationally and for composites and thermoset plastics the design and chemical composition of the material excludes conventional recycling completely as an end of life option (10). The presence of additives in many plastic products results in a recylcate with unknown impurities, some of which are toxic and they may be unnecessary or undesirable for the secondary uses of the material.

Closed-loop recycling, returning materials back to their original use, is prevented by product designs that irreversibly combine different types of materials, but also by waste collection and separation processes and the recycling processes themselves. These three aspects of waste management can be addressed by proactive product design, policy action regarding waste collection and recycling infrastructure and engineers and scientists motivated to create new recycling technologies.

Solvents can be used to selectively dissolve waste polymers at end of life for the separation of mixed wastes and composites. The advantage of this technology compared to mechanical recycling is that it is capable of returning a plastic with the same quality as virgin materials as judged by tensile strain and other properties. Recyclate specification sheets often include space for this technical information alongside a description of its appearance (such as colour and particle size) (11). Quality control and the communication of recycle properties is important to ensure the most value is obtained when deciding what materials are used to make products. Chemical recycling is another alternative recycling technique that takes material a step further back in the production chain by depolymerising it back to monomers (12). This is advantageous for polymers that degrade during use, including biodegradable polymers wrongly captured by recycling practices or that are unstable at the elevated temperatures used in recycling processes. Chemical recycling can potentially be solvent free but in many examples a solvent is required to homogenise the polymer with reactants and catalysts.

In this work, three important case studies will be discussed where a solvent-based process is used to recycle a polymer. The emphasis is on commercial applications, exploring their advantages and limitations. For a theoretical examination of polymer solubility and the related phenomena of gelation and swelling, other literature is available that provides the background knowledge for solvent-based recycling methods (13).

For completeness, it must be said there are less desirable end of life options for waste in a circular economy whereby the value of materials is significantly reduced or completely eliminated. This includes increasingly popular energy recovery (incineration), as well as biodegradation and landfill. Incineration offers some value and offsets energy demand that would otherwise likely be obtained from fossil fuels. Despite the additional use of waste material as a fuel, ultimately the material is lost. Carbon emissions and any other form of pollution represents a loss of resource and the material value it could have provided to society. Biodegradable products are designed to avoid litter. There are also some instances where it is impossible to collect a product for reuse or recycling. One example is lubricants. Forestry regulations require chainsaw and other ‘total-loss’ lubricants to be biodegradable (14). To prevent avoidable resource depletion and waste, the only articles suitable for incineration or biodegradation in a circular economy are bio-based products made only of sustainably sourced renewable materials (15).

**Solvent-Based Polyethylene Terephthalate Recycling**

One of the most ubiquitous forms of plastic waste is the plastic bottle. Typically made of PET, these
single use articles can be effectively recycled, although most often this is in an open recycling loop to make polyester fabrics. Despite this, the recycling rate of PET bottles in Europe is below capacity at only 57% (16), indicating flaws in collection and sorting. Product design also limits recycling. Once (recycled) PET is combined with other materials to make textile products, the inability of conventional recycling processes to separate the PET means there is no option to further recycle the material. For textiles consisting of a mix of cotton and PET, a solvent-based process can perform the separation and recovery of both components.

There are a large number of patented procedures for recycling textile waste containing mixed polyester and cotton items, typically clothes. A solvent can be applied to selectively dissolve either cellulose or PET. The remaining, undissolved polymer can also be recycled after filtration and drying or alternatively converted into a derivative compound. To selectively dissolve cellulose, the solvents used to make rayon fibres are applicable, such as N-methylmorpholine N-oxide (NMMO) which is used in the Lyocell process. The high flammability and oxidising potential of NMMO does not make it an ideal solvent from a safety point of view but it is typically recycled within processes with high efficiency. It has been reported that processes dissolving the PET component of composite textiles, for example in sulfolane (17), reduce the quality of the cellulose fibres (18). Nevertheless, the difficulty in dissolving cellulose has meant research efforts have focused on the solvent-based recovery of PET from textiles rather than the cotton.

Worn Again is a UK-based company that has developed technology for the closed-loop recycling of PET from textiles. A demonstrator pilot plant is due to be operational in 2021 (19). The principal technology describes a solvent added to blended polyester-cotton textiles at an elevated temperature (for example 100°C) (20). Suitable PET solvents include aromatic esters and aldehydes, as well as dipropylene glycol methyl ether acetate. Hot filtration removes undissolved cellulose from the solution of PET. The polyester is obtained with the use of isopropanol acting as an antisolvent. Characterisation of the separated polymers is not available, aside from a statement in the patent that the recovered PET has an identical infrared (IR) spectrum to the virgin material (20). Other works indicate that dissolution-precipitation cycles do not impact the polymer molecular weight, but the crystallinity of the recylcate is significantly lower than virgin PET (21). Here N-methyl-2-pyrrolidone (NMP) was used as the solvent and an alkane for the antisolvent. The use of reprotoxic NMP is not sustainable in the presence of tightening regulations (22) and the forced precipitation by antisolvents is probably responsible for the crystallinity of the isolated polymer. Greater attention is needed at the precipitation phase of the process to produce higher quality polymers.

Worn Again has also patented a procedure for recycling PET packaging, including drinks bottles (23). The key innovation that distinguishes this from mechanical recycling is the removal of dyes that otherwise dictate the quality of recylcate (Figure 1). Synthetic textiles are also appropriate feedstocks for this process. Coloured plastics and dyed textiles are far less valuable as a secondary feedstock for products compared to uncoloured transparent materials. The Worn Again technology is based on a solvent or temperature switch to firstly dissolve any dyes (but not PET) and then the polymer is dissolved at a higher temperature or in a different solvent. It is important that the first solvent swells but does not dissolve PET under the operating conditions. For instance, dyes are dissolved in ethyl benzoate at 120°C and liberated from the swollen plastic. After removing the dye solution, a second batch of ethyl benzoate is added at 180°C to dissolve the polymer. It is necessary to implement this second step to remove any insoluble impurities. For this to be economically viable the solvent will need to be recycled and in this regard the process is simplified by using the same solvent throughout. A PET recovery of 96% is satisfactory.

Solvents described as able to dissolve PET are provided in Table I (20, 23). Due to solvent residue potentially trapped in the recylcate, it is important to consider toxicity as part of solvent selection. The CHEM21 solvent selection guide categorises hazards into safety (S), health (H) and environmental (E) impact using a 1–10 scale where high scores reflect severe hazards (24). Benzyl acetate and ethyl benzoate are listed as having the best health and safety profile. High boiling solvents such as these are penalised in the environmental category because recovery by distillation is energy intensive. Depending on the proposed applications of the recycled PET, residual solvent limits for food contact applications or other regulations must also be considered.
Ultimately any disruptive PET recycling technology needs to provide significant advantages over efficient and widely practiced conventional mechanical recycling processes. The ability to separate combinations of materials is a crucial aspect of solvent-based recycling. With still much to be done to improve recovery rates of easier to recycle products, new technologies will only become commonplace if there is a political will to approach very high, near complete recycling rates, including composites.

**Solvent-Based Polylactic Acid Recycling**

Recycling techniques primarily aim to preserve the chemical structure of materials, but polyesters, with their susceptibility to hydrolysis and alcoholysis,
Alcoholysis of PET is a favourable chemical recycling approach because its reaction with ethylene glycol produces bis(2-hydroxyethyl) terephthalate as an appropriate monomer to remake PET. Alternatively methanol will produce dimethyl terephthalate and ethylene glycol which can be combined as they are to produce virgin PET (25). Hydrolysis creates an aqueous solution of terephthalic acid and ethylene glycol which thermodynamically discourages esterification.

Chemical recycling is appropriate when other recycling methods produce a poor quality recyclate. This could be due to contamination that is possible to remove during chemical recycling or because the polymer is prone to decomposition. PLA is thought to be responsible for both these issues by the recycling industry. As a biodegradable polymer, mechanical recycling causes degradation into shorter fibres and as a polyester it is also likely to contaminate PET recyclate. However, PLA is suited to chemical recycling. Hydrolysis or alcoholysis produces a single monomer and it is more rapidly decomposed than PET. This means PET waste destined for recycling can be pretreated to remove any PLA by chemical recycling. It has also been shown that mixtures of PLA and PET can be sequentially chemically recycled into their respective monomers in a two-step process so that the polymers no longer contaminate one another (Figure 2) (26). This concept proves useful where conventional sorting techniques (such as near-IR) cannot distinguish between polyesters (27), although new analytical systems are being developed to address this (28).

Although recycling PET mechanically without the need for depolymerisation or solvents is the prevailing technology, interest in alternatives is increasing, for example by Carbios, France and DEMETO, EU Framework Programme for Research and Innovation Horizon 2020. The understanding of PLA chemical recycling is arguably more advanced, but commercialisation is constrained by the small market share of PLA and the types of product it is used in. Many PLA containing products are designed for composting at end of life (for instance, plastic lined disposable coffee cups, transparent films for food packaging and other applications). As a bio-based polymer, PLA films are suitable for composting in a circular economy (if other end of life options that preserve more value are not accessible) as there is no net loss of material or emissions from a material perspective. Having said that, there are also many other components and articles made of PLA that will not biodegrade in the conditions provided by industrial composting units (PLA is not suitable for home composting). Thicker PLA materials, such as those that result from three-dimensional (3D) printing with PLA filaments are unlikely to be adequately decomposed by biodegradation on a viable timespan. The possibility that PLA is collected together with PET waste is increasing with the advent of reusable PLA drinks bottles, creating a reason to consider chemically recycling PLA.

Fig. 2. Two step chemical recycling of PLA-PET mixed waste; A co-collected PET and PLA; B zinc acetate catalysed alcoholysis of PLA; C filtration of methyl lactate solution; D isolation of methyl lactate after evaporation of excess methanol; E PET recovered; F zinc acetate catalysed alcoholysis of PET; G isolation of bis(2-hydroxyethyl) terephthalate
Zeus Industrial Products, USA, has patented a process for depolymerising PLA using conditions where PET is unreactive (29). An inert solvent (chloroform) is added to the polymer, along with reactant (methanol) and catalyst (tin dioctanoate) to complete depolymerisation at 57°C. Disadvantages of this process include the use of chloroform, which is toxic if inhaled and suspected of causing cancer and reprotoxicity (24). Full depolymerisation also requires several hours (30).

The Futerro LOOPLA® process (a joint enterprise formed by Galactic, Belgium and Total, France) is another method for chemically recycling PLA. The company has expertise in PLA production as well as its hydrolysis and alcoholysis at end of life. Either chemical recycling method is potentially able to remake a feedstock suitable for PLA production (31). Hydrolysis can occur in a solution of PLA in ethyl lactate at 130–140°C (32). Ethyl lactate is a significantly less hazardous solvent than the chlorinated solvents that are often used to dissolve PLA and other polyhydroxyalkanoates (24, 33). Without the addition of a catalyst, 97% recovery of lactic acid (isolated by crystallisation) is achieved with minimal hydrolysis of the solvent. Potential contamination by PE, PP or PET is resolved because ethyl lactate does not dissolve these polymers, which can be used advantageously to separate PLA from other plastic wastes by hot filtration. If ethanol is added to the recycling process instead of water, alcoholysis occurs (34). The product is identical to the solvent, ethyl lactate, and so separation is simplified. Distillation removes excess ethanol and residues (such as pigments and contamination). An acid catalyst is required and triaza[bicyclododecene] is preferred.

An issue with the described recycling procedures is the product (lactic acid or its esters) is subject to racemisation which produces inferior polymers with lower crystallinity (12). This must be controlled in order to perform closed-loop recycling. Furthermore, the electricity demand is too high for chemical recycling to compete with mechanical recycling (35, 36). While this is a valid concern for PET, mechanical recycling is not appropriate for PLA anyway due to its degradation (37). The first major barrier preventing chemical recycling of PLA being operated at any appreciable scale is the lack of feedstock and therefore an absence of designated PLA waste collection (38). However, the market growth of PLA products indicates future measures to capture PLA waste will need to be implemented.

Solvent-Based Polyvinylchloride Recycling

Many solvent-based recycling research projects and pilot trials have been successful, but few are viable commercial processes because of the competition from mechanical recycling and in the case of PLA the limited feedstock. The most prominent example of a successful recycling process conducted in a solvent was the VinyLoop® process, yet after 16 years of operation the plant was closed in 2018. It is important to understand the reasons why to ensure more recycling operations do not close and waste materials are not considered a burden and unnecessarily incinerated or landfilled when more value could be obtained from them.

The VinyLoop® process took PVC waste streams, often contaminated with textiles and other materials, and selectively dissolved the PVC in an organic solvent. The PVC was then precipitated by steam-driven evaporation of the solvent which itself was recycled. The PVC was said to be of the same quality as the original material. VinyLoop® was a Solvay, Belgium, technology commercialised as a joint venture in 2002 and ran until 2018 (39). The plant in Ferrara, Italy was established to recycle up to 10,000 tonnes of waste a year, primarily cable insulation (40). In 2008 the plant was updated to treat textile composites as well. Methyl ethyl ketone (MEK) is a good PVC solvent and in the VinyLoop® process was used with the cosolvent n-hexane (Figure 3) (41). In a typical example of the process, 9.3 kg of 82% MEK, 5% water, 13% hexane was added for every kilogram of PVC. After mixing at 100°C (2.8 bar) for 10 min, a dispersant was added (0.2% relative to PVC of METHOCEL® K100, a cellulose ether). The dispersion agent was needed to make fine particles of PVC. Then the temperature and pressure were reduced and steam injected (3.6 kg per kilogram of PVC). The addition of water allowed evaporation of a MEK-water azeotrope. Precipitation of PVC occurred at 64–65°C, below the boiling point of the azeotrope. Over 99% of the recovered PVC was able to pass through a 1 mm sieve. The water-MEK-n-hexane mixture was also collected. The presence of n-hexane improved the separation of the organic phase from water for reuse. An earlier patent describes the addition to salts to achieve the same effect (42).

The PVC waste being processed had been plasticised into flexible products. The VinyLoop® process maintained the additive composition of
the PVC, which in theory may be advantageous for closed-loop recycling, but in practice the ability to introduce new additives to create new products for contemporary markets and meet changing regulatory requirements would have been preferable. It was the latter that caused the closure of the VinyLoop® plant. Phthalate esters are used extensively to plasticise PVC. The toxicity of phthalate esters has prompted action by the European Chemicals Agency (ECHA), resulting in a ban on many phthalates, including bis(2-ethylhexyl) phthalate, since 2015 (43). The European Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) regulation that dictates the nature of bans or restrictions on chemical use requires any company producing, importing, using or isolating bis(2-ethylhexyl) phthalate (present above 0.1%) to have obtained authorisation to do so (44). Recycling of materials containing substances subject to authorisation is also within scope of the REACH regulation. How much this is appreciated, adhered to and policed in Europe is a subject of interesting debate with significant consequences. The operators of VinyLoop® did have authorisation (45), but these permits are time limited, in this case less than three years. As the expiry date of the authorisation drew near, the recycling plant was closed. The expectation is that most companies will stop handling the banned substances and find alternatives where possible because authorisation is very expensive to obtain. For a recycler, they are subject to the nature of waste produced by others, including legacy materials and plastics produced by manufacturers with authorisation to include otherwise banned plasticisers. A further complication is that medical products are exempt from the plasticiser ban and so there is the possibility of materials containing bis(2-ethylhexyl) phthalate still entering recycling streams.

This case study raises some important questions. How much PVC currently in use contains banned plasticisers? Many articles such as the cable insulation that was recycled by VinyLoop® has a long lifetime and was made before the EU phthalate bans were implemented. Can solvents remove additives in a compliant way? This question can be addressed by studying the solubility of PVC and phthalate esters. Distillation, as practiced by VinyLoop®, leaves non-volatile components unseparated (i.e. PVC and bis(2-ethylhexyl) phthalate). A condition of handling substances subject to authorisation in Europe is not to isolate or store refined batches of the chemical(s) in question without a permit. For recycling this is an issue as what can be considered an impurity cannot be removed without destroying it in situ. Incineration or chemical transformation may be suitable and legal approaches.

If a process were to be developed that could remove additives in a compliant way, the cosolvents MEK and n-hexane may no longer be the ideal combination for PVC recycling. This creates scope to reduce the hazards posed by n-hexane in particular. In solvent selection it is important to know what solvents are restricted or subject to authorisation by REACH of course. Recently some ether and chlorinated solvents have been subjected to authorisation and a large number of restrictions on how many others can be used are also in place (22, 33).
Solvent-Based Polyethylene and Polypropylene Recycling

The polyolefins PE (high and low density grades) and PP are produced in greater quantities than any other synthetic plastics. As for PET, mechanical recycling is viable because of the availability of the waste and the quality of the recyclate is appropriate for large markets. However, the high calorific content of these hydrocarbons means they are favoured as a feedstock for energy recovery plants (46). Plastic pyrolysis to make oils suitable for refining into fuels and base chemicals is being investigated as a more flexible alternative to incineration (47). The technology is proven on a multi-tonne scale (48, 49). BASF has now used pyrolysis oils made from waste plastic to feed the steam cracker at its primary chemical production plant (50). This indicates there is tangible interest in diversifying the uses of waste polyolefins.

It is also feasible to recover polyolefins from solution. Pappa et al. found xylene at 85°C dissolves PE but not PP (51). The undissolved PP could be removed by filtration and then the PE precipitated with an antisolvent (propanol). Recovery on a 3 kg scale was greater than 99% (Figure 4). The authors report no loss in performance attributes of the recovered polymers and actually an increase in crystallinity. This is unusual compared to the previous case studies (12, 21). Other research also reports that the elastic modulus of PE and PP increases while other properties are the same or slightly improved after solvent-based recycling (52). One explanation is that while recovery is high, the small losses probably represent the more soluble lower molecular weight polymers with less desirable properties.

Solvent-based recycling can offer a major advantage when it is used for separation of wastes. Extraction of polymers from mixed waste streams with selective solubility has been known for decades (53), but it is not cost competitive with flotation and near-IR sorting. However, multilayer materials cannot be separated effectively with current technology. This must be considered as a design flaw in a circular economy, which if impossible to resolve by product designers must be addressed by recyclers. Multilayer packaging typically contains a film of aluminium and a number of plastic layers, including PE sealing layers. The use of switchable-polarity solvents can delaminate these materials by dissolving the PE (54, 55). The principle of a switchable-polarity solvent is based on a hydrophobic amine that is converted into an ammonium bicarbonate solution with the addition of water and carbon dioxide (Figure 5) (56). The resultant hydrophilic antisolvent precipitates the PE. Releasing the carbon dioxide pressure then reforms the original amine ready for reuse.

Conclusion

Current policies and investment for waste collection, separation and recycling limit the circularity of materials. Product design, consumer choices and conventional business models also share the blame. Despite academic interest in novel polymers designed to self-heal, rapidly biodegrade or depolymerise on command, they are met with resistance by established petrochemical plastic markets. The major reason is that new, synthetically complex products will be more expensive. The introduction of new plastic materials also increases the complexity of the plastic waste market and that is generally unhelpful for recycling practices. Recycling rejection rates are overall already increasing in the UK, now standing at over 4% of post-consumer material collected from households (57). At end of life, small volume plastics are contamination in PET, PE and PP recycling streams, which increases the likelihood that waste is not returned to use because of the low quality of the recyclate. We see this in the...
recycling of PET, where the presence of PVC at 100 ppm can cause discolouration and degradation of the recyclate (58). Solvent extraction makes it possible to remove PVC from PET (59), in the same way that it might become necessary to remove PLA from PET waste in the future (27).

The potential of polystyrene recycling is also high (60), but recycling rates of consumer waste are low due to the very few districts willing to collect it. Significant barriers to polystyrene recycling include its smaller market size compared to the other major plastics and its low density. Expanded polystyrene is uneconomical to collect, transport and sort for this reason. A number of solvent-based approaches have been proposed to dissolve and densify polystyrene, which in turn could make recycling more economical. Limonene is an effective solvent (61, 62) and Ran et al. recently reported the use of binary solvent systems to dissolve polystyrene (63). The use of switchable-polarity solvents is also known for this purpose (64), but no commercial plants are operational at this time.

The potential for solvent-based recycling to make a significant contribution to a circular economy depends on willingness to invest in end of life processes that recycle difficult waste streams. Start-up and maintenance costs are certainly higher than a conventional recycling plant. There is a social benefit to recycling composites and layered materials that relates to the avoidance of litter, including topical concerns about ocean pollution and microplastics. Waste management of electrical and electronic equipment is infamous for exports to Africa exploiting vulnerable people and exposing them to toxic substances (65). The Basel Convention now makes this practice illegal. With responsibility now placed on treating this waste domestically, research has shown solvents assist the separation and recovery of the complex and valuable components found in these articles (66–69). Removing or at the very least monitoring additives will become hugely important to the recycling industry. Addressing brominated flame retardants is a key step in the reprocessing of electrical and electronic equipment (70, 71). Solvent-based recycling processes have been shown to successfully remove brominated flame retardants from plastics by firstly dissolving the waste and then adding a second solvent to selectively precipitate the polymers (72, 73).

Ultimately the possibility of future feedstock shortages and subsequent price increases, coupled with countries’ refusal to accept foreign waste (74), will demand a change to recycling practices beyond simply increasing the capacity of conventional processes. Whether this will occur in the short term or many decades from now depends on the prioritisation of a circular economy in the ambitions of world leaders.

![Fig. 5. A schematic of a switchable-polarity solvent being used to process PE; A PE is collected; B hydrophobic amine solvent dissolves PE (water may or may not be present at this stage); C addition of carbon dioxide (and water) forms a hydrophilic solution; D precipitation of PE](https://image.com/fig5.png)
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James Sherwood is responsible for alternative solvents research at the Green Chemistry Centre of Excellence, University of York, UK. His interests include bio-based products and the understanding of solvent effects in organic synthesis and materials processing. He was involved in the development of an EU standard defining bio-based solvents (EN 16766:2017) and has previously written about sustainable solvents and the circular economy.
Ruth Carvajal-Ortiz’s current research is centred around innovation in energy storage. She has a special focus on the characterisation of materials, molten salts and their potential applications to several industrial processes, such as metal production and recovery. Currently a research fellow at Coventry University, UK, Ruth is in charge of the molten salts recycling work package of the Custom Automotive Lithium Ion Battery REcycling (CALIBRE) consortium, a circular economy project for automotive lithium-ion batteries (LIBs) funded by Innovate UK and led by Johnson Matthey.

Ruth’s academic and industrial background includes electrochemical characterisation techniques (such as voltammetry), corrosion in metals under hydrothermal conditions and synthesis and characterisation of catalysts. She obtained her doctoral degree from the University of Manchester, UK, where she worked designing and testing an in situ molten salt electrochemical oxidation cell to measure hydrogen diffusion in zirconium alloys (1). Prior to her doctoral studies, Ruth worked with corrosion in metals involved in nuclear applications, during her MSc and as a research chemist at Trent University in Peterborough, Canada. The main project at Trent University’s supercritical water laboratory was part of generation IV (GEN-IV) nuclear reactor investigations. The aim of the project was to understand the corrosion behaviour of stainless steel in hydrothermal and supercritical conditions (2–4). The project included collaborations with the Canadian Nuclear Society in Chalk River, Ontario. Ruth’s background also includes synthesis and characterisation of catalysts such as titania, used in biofuels.

About the Research

The demand for LIBs has substantially increased during recent years and is forecast to grow almost 66% globally by 2025 for electric vehicles alone (5). This increases the need for an efficient and sustainable recycling process and circular economy system (6). Coventry University and several battery and automotive companies are
working together on a project to provide an achievable and effective way to recycle LIBs. CALIBRE is a new consortium that covers several stages (Figure 1), from ageing and end-of-life (EoL) assessment to chemical or molten salt recycling and materials regeneration. Additionally,

Fig. 1. LIB recycling circular economy project, CALIBRE scheme

Cathode: $\text{Me}^{x+}(l) + x\text{e}^- \rightarrow \text{Me}(s)$
Anode: $\text{Cl}^- (l) \rightarrow \frac{x}{2} \text{Cl}_2 (g) \uparrow + x\text{e}^-$

Fig. 2. Molten salt electrochemical cell scheme showing cathode and anode reactions during the process of metal deposition. Working electrode (WE) = half-cell where reaction occurs = cathode. Reference electrode (RE) = evolution of chlorine (oxidation) = anode
the project includes a mechanical separation and material recovery process at pilot scale, reuse and life cycle assessment.

A molten salt recycling process is part of the chemical recycling package. This process provides a novel approach that uses common molten salts as electrolytes and reaction media. The main advantage of the molten salts is their performance versatility which, given the multiple choices of battery electrode chemistries that are presently in the market, provide an improvement over current methods.

For the study, different eutectic mixtures of molten salts (7, 8) (for example sodium, potassium, lithium and calcium borates and chlorides, sodium and potassium carbonates) are tested to provide an optimised alternative or a shortcut to the hydrometallurgical, pyrometallurgical or even biometallurgical recovery of metals (such as cobalt, nickel and manganese). This approach takes advantage of the salts’ electrochemical and solubility properties. Initially, a two-phase molten salt system composed of sodium borate and sodium chloride was employed to evaluate the feasibility of metal recovery from mixed feeds of oxides of cobalt, manganese, copper and nickel mixtures and virgin cathode materials (for example nickel manganese cobalt (NMC) 111) by electrodeposition. The process operates within a temperature range of 800–900°C, where both salts are in liquid state. Amietszajew et al. reported 98–99% metal purity for single metal oxides deposited using the process described (Figure 2) (9, 10).

The system has demonstrated stability and could be used together with other metal recycling sources and processes. Additional insight into the environmental impact of the pilot scale process such as its carbon footprint and its efficiency are also being assessed. The new method might solve some of the issues related to the hydrometallurgical methods currently used by the recycling industry, including significant water waste, sulfate byproducts and toxic acids that are detrimental to the environment. Furthermore, the method developed is inclusive of a range of metals, which is of high importance considering the growing and future complexity of the battery waste stream and the need for the world to recycle essential materials, while at the same time reducing pollutants and greenhouse gas emissions.

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Assessing the Role of Big Data and the Internet of Things on the Transition to Circular Economy: Part I

An extension of the ReSOLVE framework proposal through a literature review

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The debate about circular economy (CE) is increasingly present in the strategic agenda of organisations around the world, being driven by government agencies and general population pressures, or by organisations’ own vision for a sustainable future. This is due in part to the increasing possibility of turning original theoretical CE proposals into real economically viable initiatives, now possible with modern technology applications such as big data and the internet of things (IoT). Information technology (IT) professionals have been called upon to incorporate technology projects into their strategic plans to support their organisations’ transition to CE, but a structured framework with the necessary IT capabilities still lacks. This study focuses on taking the first step towards this path, by extending the technology attributes present on the existing Ellen MacArthur Foundation (EMF) Regenerate, Share, Optimise, Loop, Virtualise and Exchange (ReSOLVE) framework. The research was conducted based on an extensive literature review through 226 articles retrieved from Scopus® and Web of Science™ databases, which were triangulated, validated and complemented with content analysis using the ‘R’ statistical tool, grey literature research and inputs from specialists. Part I describes the introduction and methods used in this study.

1. Introduction

IT plays an important role in enabling disruptive organisational transformations, despite the known privacy and confidentiality issues and security risks (1, 2) constantly being run up against with the use of technology itself (3). Recent studies show decision-making processes have become much faster and more precise in companies adopting big data technologies (4, 5) for example. Internal and external communications and knowledge sharing (6, 7), not only in large organisations but also in small and medium-sized enterprises (SMEs) (8), are faster and better due to social networks (9) and instant messaging technologies (10), just to mention a few recent examples. In the corporate sustainability (CS) and other environmental fields it is no different. Many recent studies focus on understanding the role of IT in offering solutions to reduce the negative impacts of organisations and society on the environment (11–13), including those generated by modern technologies, known as ‘green IT’ (14–17). Several other studies can be found in the literature. Large data vulnerability...
risks are also present in this context (18). One special concept based on the planet’s sustainability issues is gaining attention from organisations and government recently, namely CE. Although the concept of CE has existed for decades, it has become more evident in the past few years as resources are becoming scarcer and more expensive, mainly because world population and resource consumption continue to grow for a limited-resource earth. Moreover, society is now more concerned about issues such as global warming, plastics and other waste disposal (19, 20) and aware of the need for stewardship of our planet’s natural resources (21). Another relevant factor is the quick development of automation technologies brought by what has been called the Fourth Industrial Revolution, also known as Industry 4.0, essentially leveraged by big data and the IoT, which are making the implementation of CE concepts not only possible and more economically feasible, but necessary (22, 23).

The role big data and IoT perform in enabling the transition to CE has been subject of many studies and is attracting the interest of the scientific community. As organisations and governments are being pushed to take action to transform business and city models to enable CE, more efforts need to be taken in technology by IT professionals to make it a consistent, fast time-to-market and low-cost transition (24–28). However, the IT path to be followed by organisations and governments still lacks a structured framework, with some practitioners even questioning whether technologies such as big data really foster sustainability (29). Researchers have been putting a lot of effort into establishing CE theories and models to provide useful and usable tools to help scientists and practitioners develop their work. Nevertheless, as such initiatives are usually undertaken independently and motivated by different interests, dozens of separate studies have arisen in recent years. Although CE has been known since the 1970s, more than 50% of all studies are published since 2014, as shown in Figure 1. Recent studies show more than 100 CE definitions have already been documented and published (30), along with dozens of frameworks, each one approaching CE from a different perspective. Although all offer significant contributions to science and practice, choosing one to perform as a baseline for research and business strategies development is challenging. When the IT component is added, the situation becomes even more complex, as new disruptive technologies arise very fast and accelerate the obsolescence of previous studies. Moreover, it is being noticed that current CE frameworks rarely explore the IT component (or ignore it, as described in Section 2.2), giving modern and disruptive technologies a secondary role on the transition to CE. An exception is the EMF ReSOLVE framework (31). It not only acts as a basis for other published frameworks, but also recognises the greater role IT performs in the transition to CE, yet it still lacks theoretical deepening, which is a gap to be addressed by this research.

![Figure 1](https://doi.org/10.1595/205651319X15643932870488)
This study intends not only to reinforce the key role technology performs on the transition to CE – specially big data and IoT, both the foundation of the so-called Industry 4.0, as already presented in some novel published studies (32, 33), but also proposes a preliminary framework for IT capabilities, built on EMF’s ReSOLVE framework, to be used by IT professionals in order to understand and assess their organisation’s gaps for the transition to CE. The framework was conceived based on a literature review composed of four separate sources: a traditional review of 226 big data or IoT applications on CE scientific articles, all retrieved from Scopus® and Web of Science™ databases; content analysis (simple bibliometric review) of the retrieved articles; industry, corporate and government initiatives (grey literature); and industry experts review. This triangulation was a necessary step not only for validity and reliability issues, but also because of the known gap between the academy and industry and private sector initiatives for the research subject (19), so each source provided complementary data. Therefore, this study aims to answer the following research question: What are the big data and IoT capabilities that IT professionals need to address in order to support their organisations in the transition to the CE?

The remainder of the paper is organised into four sections, starting with the literature review, including an analysis of the current CE available frameworks, followed by the methodologies applied to the research and a results and discussion section including the proposed IT capabilities framework. The final section (in Part II, (34)) presents the study’s conclusions, its limitations and future research recommendations.

2. Literature Review

2.1 Defining Circular Economy

For the past few years, the current production and consumption model essentially based on a linear flow (take-make-dispose), which generates an increasing throughput of natural resources, has brought back a concept originating during the 1970s and closely related to environmental concerns: CE. It is based on a circular system where both organic and technical wastes are minimised and returned as feedstock, leading to a zero waste generation model (20, 35–37), being restorative and regenerative by design and resting on the following principles: preserving and enhancing natural capital, optimising resource yields and fostering system effectiveness (38). The efficient use of energy (and its transition from fossil to clean and renewable sources) and the promotion of product reuse and lifetime extension actions also contribute to CE.

Currently only 9.1% of the world economy can be considered circular (39), meaning that around 90% of everything that is produced and consumed on the planet still follows the take-make-dispose flow. Furthermore, the world population continues to grow for a limited-resource earth (19, 20) with scarce commodities becoming more expensive (40). For instance, if we look at Brazil alone, only 1% of all organic waste is treated and beneficiated in a country where 50% of all wastes are organic, producing every year the amount of greenhouse gases equivalent to seven million cars (41).

Recently the United Nations Environment Programme (UNEP) developed a study focused on the issue of disposal of plastics in the ocean that led to the ‘Marine Plastic Debris and Microplastics: Global lessons and research to inspire action and guide policy change’ report. (42). Some estimates from the report indicate that the ‘visible’ part of marine debris (what is floating on the sea’s surface) represents only 15% of all marine debris while those on water columns account for another 15% and 70% of all marine debris is simply resting on the seabed. Moreover, most of this plastic breaks up into microplastic over time, representing a hazard to wildlife, fish and people.

These and many other documented facts demand action from governments, organisations and society, and CE is performing a critical role in this necessary transformation. For example, in 2018 the European Commission – the executive branch of the European Union – launched the 2018 Circular Economy Package, which is a set of measures aiming to transform Europe into a more sustainable continent (43), including challenging goals such as making all plastic packaging recyclable by 2030. It consists of several documents focused in legislations about plastics, waste and chemicals and proper communication to citizens. This was an outcome of the EU Circular Economy Action Plan established two years before. China is also making considerable progress transitioning to CE, being one of the first countries to have laws for CE development (after Germany and Japan) since 2009 and further detailed in 2013 with its Circular Economy Development Strategies and Action document, establishing directives for companies, industrial parks and even cities and regions (44).
In addition, not only can CE address social and environmental issues, but it can also help develop the economy. In Europe alone, benefits of around €1.8 trillion may be achieved by 2030 (45).

Those and other initiatives led a number of organisations, including public administration and academia, to put more effort into developing or applying solutions and research to promote the transition from the linear to the circular model economy. Science has recently made significant progress in CE research. This can be seen by observing the academic research evolution presented in Figure 1, which shows that most CE research is relatively new (26% in 2017 and 2018 alone).

Nevertheless, as a consequence, a number of different theories and principles or constructs are still emerging, making the process of defining CE formally difficult. Therefore, one of the challenges faced by scholars is agreeing on a common theoretical scientific definition of CE and its various ramifications, as most of the successful initiatives have been almost exclusively led by practitioners.

Discussions about the concept’s incipience have already been the object of recent studies. For example, recent research put together 114 different CE definitions and coded them on 17 dimensions (30). Other studies propose taxonomies based on different methods (19, 46), while others try to establish a consensus for the adequate use of the term CE (47) and compare it to the concept of sustainable development (36). There is also some justified criticism regarding the correct use of the term CE (48) and even questions whether CE captures the environmental value propositions (49).

For this research, we identified a straightforward classification based on a comprehensive literature review article covering 20 years of CE studies, that groups it into six basic principles (20): (a) design, (b) reduction, (c) reuse, (d) recycle, (e) materials reclassification into technical or nutrients and (f) renewable energy. The study had more than 300 citations in three years since its publication in the Journal of Cleaner Production (ISSN 0959-6526), which is a very high impact factor journal. Details on each principle obtained from the literature can be found in the original publication.

2.2 Circular Economy Frameworks

There are several CE frameworks available in the literature. A query in Scopus® with the expressions ‘circular economy’ and ‘framework’ in title, keyword and abstract retrieved 21 different models, the oldest published in 2016. Of those, we compared the nine most relevant ones (i.e. from journals with scimago >20 and with at least five citations), which are presented in detail in Appendix 9 (for all Appendices: see the Supplementary Information included with the online version of this article). Here we describe the top three: the most popular; ‘A comprehensive CE framework’ (50) was proposed through an extensive literature review and is based on economic benefits, environmental impact and resource scarcity and is focused in the manufacturing industry. The second is called ‘The 9R Framework’ (30). It extends the classical concept of 3Rs to nine definitions and suggests an increase of circularity for each one: Recovery of Energy (less circular: incineration), Recycle, Repurpose, Remanufacture, Refurbish, Repair, Reduce, Rethink and Refuse (more circular: make product redundant). The third, ‘Circular economy product and business model strategy framework’ (51), proposes the need for design and business model strategies to be implemented in conjunction in order to better drive circularity. Although all are unique and proved to be valuable given their popularity, along with authors and publications relevance, two common characteristics were observed: they do not consider the ‘technology’ aspect; and all reference directly, as a main source of information, the EMF, known to lead and foster both theoretical and practical initiatives regarding CE since 2010. EMF created a framework called ReSOLVE, which is used as a basis by some of the top frameworks mapped (for example, the backcasting and eco-design for the circular economy (BECE) framework (52)) and is the most popular in internet search (see Appendix 9).

It is considered part of the grey literature rather than a scientific document. It offers organisations a tool for generating circular strategies and growth initiatives, composed of the levers: (a) regenerate, (b) share, (c) optimise, (d) loop, (e) virtualise and (f) exchange. Moreover, technology is key: transformation of products into services, leveraging big data and automation and incentives to adopt new technologies (for example, three-dimensional printing) are all aspects considered by the ReSOLVE framework. Therefore, rather than proposing a new framework in this study, the authors decided to build the model on ReSOLVE.

2.3 Big Data and Internet of Things

The big data concept represents the ability to gather, process and analyse massive amounts of structured and non-structured data continuously (53, 54),...
transforming it into useful information for decision-making activities. Researchers have reduced the definition into the basic 4Vs (55, 56): (a) volume, (b) variety, (c) velocity and (d) veracity, representing its main characteristics. Other scholars have improved the definition and extended it with: (e) value (57, 58), (f) validity, (g) visualisation, (h) vulnerability, (i) volatility and (j) variability (59). Big data has already proved its importance for organisations, as for example in the health industry (60), general management (61) and government (24).

IoT is an emerging technology that enables data acquisition, transmission and exchange among electronic devices and targets enabling integration with every object through embedded systems (62). It has three main components: asset digitisation, asset data gathering and computational algorithms to control the system formed by the interconnected assets (63). One relevant data source may be considered for big data. Not only can it support applications such as providing better disease diagnostics and prevention, monitor stocks in real time (64) or aid the transportation of goods, but it also applies to basically any activity involving data monitoring and control, and information sharing and collaboration (65). This emerging term is considered key to enable technological solutions and is receiving industry-specific extensions such as in mining (metallurgical internet of things (m-IoT)) (66), industry (industrial internet of things (IIoT)) (67) and for environmental causes (environmental internet of things (EIoT)) (24, 68).

There are other concepts related to CE being leveraged by big data or IoT. They are described in Table I. In the context of CE for this research, servitisation relates to the reuse principle. It improves asset usage rates to their highest utility and value as the product ownership remains with the manufacturer, who is responsible not only for the proper product collection and disposal, but also for extending its lifetime and recapturing value through refurbishment and reuse. Sharing economy also explores the reuse and reduce principles as product owners can collaborate with each other in order to maximise the use of their own assets during their idle periods. For example, studies show cars stand idle for about 95% of the time (69). Smart cities relates essentially to the design principle as it consists basically in planning and reorganising urban areas.

### 3. Methodology

In this section, all methods applied in this study are explained to ensure research replication and allow validity and reliability confirmation (111, 112). Also, in order to establish an acceptable degree of reliability in the research, the data analyses were triangulated (112) through different methods and techniques as necessary for social science literature reviews (113) to provide a consensus regarding the proposed capabilities list: traditional literature review, basic content analysis, grey literature mapping and experts review and confirmation (proposed model presentation and conformity verification), thus reducing the risks of common biases from inaccurate or selective observations and overgeneralisation (114), as shown in Figure 2. Details for each step are presented below.
3.1 Data Collection: Scientific Papers

Data collection from scientific databases consisted in two basic steps: data source identification and data extraction criteria definition.

Although some previous published research used only one database source, for this study we combined data from two relevant and robust databases. The first was Scopus®, which is considered to be the largest abstract and citation database of peer-reviewed literature, while the second independent and unbiased database was Web of Science™, known as one of the largest citation databases available and the first in the market. Both provide significant results for English-language journals according to comparative studies (115) and are very consistent with each other (116).

The same query logic was applied for both databases, along with the same filters and constraints, following the recommendations found in a previous published study, thus using similar expressions and precautions with specific taxonomies (19). Query logic for both CE and big data or IoT expressions are shown in Figure 3 and were applied for document title, keywords or abstract. Coding of key terms and themes to represent both CE and big data or IoT on database queries were obtained from previous research (19) in the absence of a comprehensive taxonomy and are reproduced in Appendix 5. Coding categories criteria are presented in Appendix 6 and the complete and detailed results in Appendix 7. After running the independent queries individually for both databases, the results were combined, generating an integrated result of 370 unique documents for analysis. At this point, no restrictions to document types or relevancy had been applied.

Step two consisted of applying the authors’ analysis to eliminate incoherent documents. In order to avoid author biases during this phase, objective criteria for document elimination were defined: items retrieved from keywords or abstract but with no direct relation to document contents (for example, abstract mentioning, but document not about big data – term appears in abstract but is not related to it); term appears in document body but as a future research recommendation or indirect implication; namesake term used (such as ‘blue economy’). A total of 110 documents were removed from the set after reading. This represented an improvement from previous research (19) that focused only on the bibliometrics part without applying authors’ detailed in-depth proofreading and review. Then, non-applicable items such as conference reviews, errata or documents with no content were also discarded, representing a total of 29 documents. Finally, a total of five documents not in English were removed. The final set of documents used in the research consisted of 226 documents. The complete filter process is presented in Figure 4.

Previous literature review research was consulted to try to identify other criteria to narrow the number of documents to be analysed to the most relevant. Cut-off methods based on scientific recognition were mapped (48, 117, 118), some of them applying Pareto principles to focus on the most cited articles and author research relevance. Nevertheless, as shown in Figure 1, most of the papers retrieved were less than two years old, so relying on scientific recognition by number of citations could have produced undesirable results. Because of this the authors decided to analyse the entire set of articles (226 documents) for this research.

3.2 Scientific Literature Review

Documents were classified according to the following criteria: country and region (Scopus® and Web of Science™ databases do not retrieve
Circular economy query:

\[
\text{TITLE\_KEYWORD\_ABSTRACT = (\langle List\ of\ Terms \rangle\ OR \ "Reduc*" AND "Reus*" AND "Recycl*"\) AND ("sustainability" OR "sustainable") OR (\langle Circular\ economy-like\ unique\ terms\rangle\) OR AND PUBLICATION\_YEAR <=2018}
\]

Big data/internet of things query:

\[
\text{TITLE\_KEYWORD\_ABSTRACT = (\langle List\ of\ Terms \rangle\ OR (("Spark\ Streaming" OR "MLib" OR "Spark\ R" OR "Machine\ Learning") AND "Apache") OR (\langle Hdfs\ OR "Cfs"\ AND "File\ System\rangle\) OR ("Mizan\ AND "Kaust") OR ("Presto\ AND "SQL")\) AND PUBLICATION\_YEAR <=2018}
\]

Fig. 3. Query logic for Scopus® and Web of Science™, adapted from previous published research with the use of the same lists of terms (19).

Fig. 4. CE and big data or IoT documents search summary.

(*)Non-related documents: items containing the query keywords but with contents not related to the research subject.)

country names. Documents were assigned to countries according to (in this order of priority): author affiliation, main author affiliation, conference location, journal location or source title location, using the same criteria applied in prior research (19)); methodology type, in compliance with similar literature review research (119), composed of: (a) theoretical and conceptual papers, (b) case studies, (c) surveys, (d) modelling papers and (e) literature reviews; industry, according to the Standard Industrial Classification (SIC) codes assigned by the
US government to business establishments to identify their primary business (120); and related CE principle according to the classification mapped for this research (20), divided into: (a) design, (b) reduction, (c) reuse, (d) recycle, (e) reclassification and (f) renewable energy.

Due to the considerable number of documents used in the review (226 after initial screening), the complete list with corresponding classifications is available in Appendix 7.

3.3 Triangulation: Content Analysis with Word Cloud

Word cloud is a tool that generates a visualisation in which the more frequently used words in a given text are highlighted. Although it provides good presentation and is visually appealing, it does not provide useful information when applied alone, but can perform well as a supplementary tool to help confirm the findings and related interpretations (121). So to support the research results confirmation, all 226 documents selected were converted into a robust text corpus and went through data mining with the support of ‘R’ statistical tool (122), so that expressions of more occurrences were ranked.

In order for the analysis to be accurate, compound expressions (bigrams, trigrams and four-grams) were bound together into single words prior to word cloud execution. Despite the existence of formal methods and patents for automated compound expressions generation (123), the authors decided to create the database manually due to the heterogeneity of subjects under analysis (i.e. CE, big data, IoT), so automatic conversion risks were avoided. The complete list is available in Appendix 4.

The authors then cleansed the results according to the following steps: (a) concatenation of expressions (for example, big data to bigdata); (b) unification of same meaning of words (for example, recycling and recycled for recycle); (c) separation of similar word with different meanings (building not the same as build); (d) removal of punctuation, numbers, URLs; (e) case conversion; (f) singularisation (for example, feet unified with foot); and (g) removal of stop words (function words such as ‘which’, ‘the’, ‘is’, ‘in’, verbs and auxiliary words) based on International Organization for Standardization (ISO) and snowball sources (124), combined with a customised list compiled by the authors and also shown in Appendix 4. The word cloud image was also generated with ‘R’.

The following libraries were used in the analysis: ggplot2 (125), githubinstall (126), pluralise (127), RWeka (128, 129), SnowballC (124), stopwords (130), tm (131, 132), wordcloud (132).

3.4 Grey Literature Mapping

There are a number of non-academic institutions, such as government agencies, private businesses and non-governmental organisations (NGO) developing successful practical CE initiatives that need to be taken into consideration as both the subject matters – of CE and big data or IoT – are still emerging and evolving scientifically. Finding literature and information on this particular area of research required the use of non-scientific sources (134). Moreover, recent studies indicate that there are benefits for including grey literature in reviews: overall findings enrichment, bias reduction and to address stakeholders’ concerns (135), which are all relevant for this research. Furthermore, there is known to be a gap between the academic world and practitioners for this research subject (19).

The complete list of supplementary grey literature sources used to enrich the analysis is presented in Appendix 3.

3.5 Triangulation: Experts Review

The resulting preliminary framework was submitted to a group of eight domain experts who individually analysed the capabilities to assess the content clarity and representativeness, and to provide insights on items that could be revised or added to the list so that the authors could map additional research sources to be studied. The domain experts were selected first according to methods presented in the literature: type of knowledge, type of service and type of expertise (136). After identifying the experts, accessibility was considered as a second filter. A few conflicts identified were addressed with additional grey literature confirmation and were considered positive as they are common and important in social sciences (137). Expert contributions not verified in the literature were discarded. The list of domain experts is presented in Appendix 2.

Part II (34) will describe the results, conclusions and future recommendations of this research.
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Appendices

The following Appendices may be found in the Supplementary Information included with the online version of this article:

Appendix 1 Top publications by source (scientific journals with more than one publication); publishing institutions; top journal articles on circular economy with the use of big data or IoT ordered by year / author
Appendix 2 Participating domain experts consulted during capabilities validation phase
Appendix 3 Grey literature used in the research
Appendix 4 Word cloud generation considerations
Appendix 5 Complete query logic reproduction for both Scopus® and Web of ScienceTM databases
Appendix 6 Coding categories criteria for the 226 mapped documents
Appendix 7 Complete document list with corresponding attributes mapped
Appendix 8 Selected practical case studies mapped during the literature review
Appendix 9 CE frameworks
Appendix 10 Statistical software ‘R’ code applied

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This paper presents the main findings of a literature-based study of circular economy (CE) extending the technology attributes present on the Ellen MacArthur Foundation (EMF) Regenerate, Share, Optimise, Loop, Virtualise and Exchange (ReSOLVE) framework. The introduction and methods were presented in Part I (1). Part II concludes that there are 39 capabilities grouped into six elementary CE principles and five action groups, with public administration being the most interested sector, forming the CE information technology (IT) capabilities framework. It is expected the framework can be used as a diagnostic tool to allow organisations to evaluate their technological gaps and plan their IT investments to support the transition to CE.

1. Results and Discussion

For this study, a complete set of scientific publications was analysed. Regional and temporal characteristics are presented in Figure 1 (from first publication to 2018; total of 226 documents, including articles, reviews, conference papers and proceedings, filtered according to remarks presented in the Methodology section of Part I (1)) and Table 1. Europe and Asia lead the interest in the subject mostly due to the efforts and regulations established by the EU and China governments. North America (here including Mexico and other Central American countries), despite the high level of development of the geographies, occupies only the third place in publications, with less than 15% of participation. This number also draws attention to the fact the USA is one of the major environmental polluter countries according to the United States Environmental Protection Agency (US EPA) (2), which reveals a context of significant research opportunities for the region.

Considering all the publications, 53% came from scientific journals and 15 sources presented at least two publications on the subject. The Journal of Cleaner Production (ISSN 0959-6526) and Sustainability (ISSN 2071-1050) led with 19 and nine publications respectively, as shown in Appendix 1 (for all Appendices, see the Supplementary Information included with the online version of Part I (1)). The high number of other source documents (47%), along with the publication concentration in the past three years, may indicate science and academia are still in the early stages of development for the studied subjects.

The research also grouped publications according to the Standard Industrial Classification (SIC) codes (3). The majority of documents apply to public administration (32.3%), mostly because of smart city initiatives and suggests governments are leading initiatives and sponsoring research. A considerable number of publications (30.1%)
were not allocated to a specific SIC code as they could not be related to any specific industry. Results are presented in Table II.

Documents were also grouped by methodology type, which demonstrates more interest in model development and reviews as shown in Figure 2.
This indicates researchers have been putting more effort into standards, definitions, framework creation and reviews (which can be justified by the early stage of stability and maturity of the subjects). Other analysis was made according to CE principles (4) as demonstrated in Figure 3. The highest level of participation on the reduction principle suggests a major focus on changing consumer behaviour with the use of new technologies rather than investing in clean energy sources or extending product lifespans. On the other hand, the reclassification principle, despite its importance, still lacks technology efforts.

Supplementary details regarding mapped documents, such as top publishing institutions, journals and authors are available in Appendix 1. In Appendix 8 we also present some practical case studies mapped during the literature review for distinct industries and countries in order to illustrate how CE can be fostered by big data and internet of things (IoT).

### 1.1 Content Analysis

Research extracted the 150 most frequent words from the 226-article text corpus in order to verify and confirm that the resulting capabilities list is

### Table II Publications by Industry Type with SIC Codes

<table>
<thead>
<tr>
<th>Industry</th>
<th>SIC Codes</th>
<th>Number of Publications</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public Administration</td>
<td>91–99</td>
<td>73</td>
<td>32.3%</td>
</tr>
<tr>
<td>Cross industry</td>
<td>n/a</td>
<td>68</td>
<td>30.1%</td>
</tr>
<tr>
<td>Manufacturing</td>
<td>20–39</td>
<td>18</td>
<td>8.0%</td>
</tr>
<tr>
<td>Construction</td>
<td>15–17</td>
<td>14</td>
<td>6.2%</td>
</tr>
<tr>
<td>Agriculture, Forestry, Fishing</td>
<td>01–09</td>
<td>11</td>
<td>4.9%</td>
</tr>
<tr>
<td>Transportation Equipment</td>
<td>37</td>
<td>8</td>
<td>3.5%</td>
</tr>
<tr>
<td>Business Services</td>
<td>73</td>
<td>7</td>
<td>3.1%</td>
</tr>
<tr>
<td>Private Households</td>
<td>88</td>
<td>5</td>
<td>2.2%</td>
</tr>
<tr>
<td>Engineering Services</td>
<td>8711</td>
<td>4</td>
<td>1.8%</td>
</tr>
<tr>
<td>Retail Trade</td>
<td>52–59</td>
<td>4</td>
<td>1.8%</td>
</tr>
<tr>
<td>Electric, Gas and Sanitary Services</td>
<td>49</td>
<td>3</td>
<td>1.3%</td>
</tr>
<tr>
<td>Transportation &amp; Public Utilities</td>
<td>40–49</td>
<td>3</td>
<td>1.3%</td>
</tr>
<tr>
<td>Educational Services</td>
<td>82</td>
<td>2</td>
<td>0.9%</td>
</tr>
<tr>
<td>Mining</td>
<td>10–14</td>
<td>2</td>
<td>0.9%</td>
</tr>
<tr>
<td>Chemicals and Allied Products</td>
<td>28</td>
<td>1</td>
<td>0.4%</td>
</tr>
<tr>
<td>Computer and Office Equipment</td>
<td>357</td>
<td>1</td>
<td>0.4%</td>
</tr>
<tr>
<td>Food and Kindred Products</td>
<td>20</td>
<td>1</td>
<td>0.4%</td>
</tr>
<tr>
<td>Health Services</td>
<td>80</td>
<td>1</td>
<td>0.4%</td>
</tr>
<tr>
<td>TOTAL</td>
<td>–</td>
<td>226</td>
<td>99.9%</td>
</tr>
</tbody>
</table>

### Fig. 2. Methodologies applied on 226 mapped documents

### Fig. 3. CE principles identified in 226 mapped documents, some articles with more than one principle
addressing the most relevant topics. The word cloud generated is shown in **Figure 4**.

Bigram, trigram and four-gram generation proved to be a valuable insight resource as some compound expressions not only appeared in the top 150 list, but also performed as an important validation tool for capabilities generation (for example ‘cloud computing’, ‘energy consumption’ and ‘smart sustainable city’), all key aspects of the validated capabilities list.

The top 20 expressions mapped are presented in **Table III**. The complete list of top 150 expressions is available in Appendix 4.

The words ‘product’, ‘service’, ‘urban’ and ‘city’ all appeared with high frequency, indicating initiatives for different industry types can benefit from big data and IoT, for example, and therefore influenced the framework development (i.e. specific treatment for industry type). The same analysis was made for each expression, performing essentially as a verification tool to ensure the framework and capabilities were consistent.

### 1.2 Experts Review

The first version of the resulting capabilities framework was submitted to a group of domain experts who provided useful insights into the study. **Table IV** shows the main contributions accepted from the domain experts. Typographic errors, rephrasing, use of synonyms and other small revisions are not listed.

The list of domain experts is presented in Appendix 2.

### 1.3 CE IT Capabilities Framework

The final framework resulted in a set of 39 capabilities divided according to the six CE principles and presented in **Figure 5** and **Table V**.

It builds on both the ReSOLVE framework (5) and the six CE principles (4). The mapped capabilities were separated into application groups and industries, as some are considered technological tools, others new processes, some long-term projects and others punctual actions.

The mapping considering each capability and the corresponding block of the framework is presented in **Figure 6**. Capabilities not related to any industry are considered as applicable to any (cross industry).

#### 1.3.1 Framework Highlights

The ReSOLVE Framework itself promotes a direct application of modern technologies on the elements ‘optimise’ (leverage big data and automation), ‘virtualise’ (dematerialisation) and ‘exchange’ (for example three-dimensional printing). With the establishment of the CE IT capabilities framework, not only can new applications be observed to those elements, but also it is now possible to notice that all elements of ReSOLVE can benefit from cutting-edge technologies. For example: the ‘regenerate’ element can be leveraged with net metering and the use of solar energy allows the use of IoT.
Table IV Domain Experts’ Main Contributions

<table>
<thead>
<tr>
<th>CE principle</th>
<th>Contribution</th>
<th>Contributing expert(^a)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Design</td>
<td>Clarification on urban areas relation to public administration only</td>
<td>3, 4</td>
</tr>
<tr>
<td></td>
<td>Added ISO 20400 - sustainable procurement (applies to reduction, reuse and</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>recycle principles as well)</td>
<td></td>
</tr>
<tr>
<td>Reduction</td>
<td>Process postponing: inclusion of ‘no effectiveness loss’ condition</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Decentralised offices: only if proven to provide more efficient use of available</td>
<td>4, 5</td>
</tr>
<tr>
<td></td>
<td>resources</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Added emissions monitoring</td>
<td>4</td>
</tr>
<tr>
<td>Reuse</td>
<td>Added marketplaces for sourcing, value and managing reusable materials</td>
<td>1</td>
</tr>
<tr>
<td>Recycle</td>
<td>Added disassembling and remanufacturing</td>
<td>4, 6</td>
</tr>
<tr>
<td></td>
<td>Policies application rather than only having the policies documented</td>
<td>1, 4</td>
</tr>
<tr>
<td></td>
<td>Use of electronic tags</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>Added recyclable resin</td>
<td>1</td>
</tr>
<tr>
<td>Renewable</td>
<td>Net metering added to list</td>
<td>4</td>
</tr>
<tr>
<td>energy</td>
<td>Blockchain transactions added to list</td>
<td>2, 4</td>
</tr>
</tbody>
</table>

\(^a\) The domain experts are identified in Appendix 2, Part I (1)

Fig. 5. The CE IT capabilities framework

Based devices in remote areas, like agricultural crops; the ‘share’ element benefits from smart connected devices monitoring equipment’s usage and providing predictive maintenance data and technology also connects users with similar interests allowing higher usage levels; in ‘optimise’, waste reduction can take many advantages from technology, varying from the use of AI and machine learning on product design to optimise resource consumption to application of green IT to increase product efficiency; ‘loop’ benefits from the use of AI to allow closing the loop on materials and to optimise waste collection and reverse logistics with IoT; ‘virtualise’ links directly with cloud computing.
### Table V Mapped Big Data or IoT Capabilities on CE Principles According to Literature Review

<table>
<thead>
<tr>
<th>CE principle</th>
<th>Big data or IoT capabilities</th>
<th>Sample sources</th>
</tr>
</thead>
</table>
| **Design (DS)** | 1. Parts made with compatible components with the support of modern technology based on artificial intelligence (AI), machine learning, big data or IoT that can be mixed after use without contamination for efficient recycling or upcycling or remanufacturing and designed for new uses, enhancing its after-use value  
2. Use of big data or analytics during product design or conception to provide sustainable feedstock and optimised resource use to reduce waste generation during manufacturing processes  
3. Product lifecycle management (PLM) concepts supported by big data or IoT to improve product design, such as modular or replaceable components  
4. Design and use of IT infrastructure for reuse or easy recyclability  
5. Use of sustainable design criteria on technology selection processes, such as design for recycle  
6. For public administration sector only: CE-planned urban areas designed and conceived according to smart city principles to optimise waste collection and value recovery with the use of IoT | (6–17) |
| **Reduction (RD)** | 1. Minimise greenhouse gas and other pollutant emissions with the support of modern technologies such as analytics for monitoring and decision making  
2. Optimise materials savings through smart connected devices  
3. Use of decentralised IT technologies to provide resource use and consumption (either energy or components) reduction, such as cloud computing with big data, avoiding the need of robust local physical infrastructure  
4. PLM concepts supported by big data or IoT to reduce waste generation and disposal  
5. Use of smart sensors to monitor energy, water and other resource consumption in manufacturing processes  
6. Use of smart sensors to monitor energy, water and other resource consumption within facilities of organisations  
7. Machine behaviour monitoring to autonomously optimise energy, water and other resource consumption, even by postponing processes if necessary, without prejudice to process effectiveness  
8. Use of IT devices and infrastructure in a way that offers minimal environmental impact (green IT) by optimising energy consumption  
9. Use of technology-enabled decentralised offices and data centres proven to provide more efficient use of available resources (including human, for example no need to commute)  
10. Use of energy savings or minimum waste generation criteria on technology selection processes  
11. Energy efficiency improvement in data centres | (7, 12, 13, 16–28) |
| **Reuse (RU)** | 1. Improve asset usage rates by applying CE business models such as leasing and ‘platform as a service’ (PaaS), enabled by IoT and big data  
2. Product lifetime extension by using connected devices to facilitate predictive maintenance  
3. PLM concepts supported by big data or IoT to improve product and component reusability  
4. Product to service (possession vs. use) transition enabled or leveraged by IT to improve usability rates  
5. Use of cloud-based marketplaces for sourcing, value and managing reusable materials  
6. IoT-enabled waste collection or reverse logistics for materials (such as packaging) reuse  
7. Monitor component location and quality in order to assess state and allow reuse  
8. Use of IT devices or infrastructure in a way that offers minimal environmental impact (green IT) by reusing components to their maximum  
9. Use of IoT devices to increase component sharing and reuse rates (such as in industrial symbiosis)  
10. Policies for extending IT infrastructure lifecycle (for example, donation)  
11. Use of product or component lifetime criteria on technology selection processes | (7, 9, 12, 13, 15–17, 25, 29–32) |

(Continued)
Table V Continued

<table>
<thead>
<tr>
<th>CE principle</th>
<th>Big data or IoT capabilities</th>
<th>Sample sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recycle (RY)</td>
<td>1. Apply AI to support ‘closing the loop’ on products and materials, allowing optimised product sorting and disassembly, remanufacturing and recycling</td>
<td>(7, 9, 12, 13, 15–17, 25, 33)</td>
</tr>
<tr>
<td></td>
<td>2. PLM concepts supported by big data or IoT to improve product recyclability</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Use of IoT technologies to optimise waste collection and reverse logistics for recycling or upcycling, including the use of electronic tags on trash bins</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4. Use of IT devices or infrastructure in a way that offers minimal environmental impact (green IT) by applying recycling policies</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5. Use of IT infrastructure recycled from electronic waste</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6. Applied policies for discarding obsolete IT infrastructure in a sustainable (for recycle) manner</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7. Use of product recyclability (or made from recyclable resin) criteria on technology selection processes</td>
<td></td>
</tr>
<tr>
<td>Reclassification (RC)</td>
<td>1. Applying IoT integrated with AI to allow mixed industrial technical (non-organic) waste automated separation</td>
<td>(7, 34–36)</td>
</tr>
<tr>
<td>Renewable energy (RN)</td>
<td>1. Use of renewable energy sources (including light, motion, temperature) for IT devices to operate autonomously, mainly in poorly accessible remote areas</td>
<td>(25, 37–43)</td>
</tr>
<tr>
<td></td>
<td>2. Power IT devices or infrastructure with renewable clean energy</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3. Net metering-based(^a) renewable energy generation, monitoring, consumption and selling (leveraged by blockchain when applicable)</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) Process of managing the entire production lifecycle from design, through engineering, manufacturing and ultimately service and usage

\(^b\) Solution where consumers generate their own power and receive credits for the excess power they produce. Excess power is delivered to the grid, so net metering can be thought of as an energy storage solution that allows consumers to push and pull energy to and from the grid

Fig. 6. The CE IT capabilities framework with mapped capabilities
and the home office; and ‘exchange’ may use technology on product design to promote shifting to renewable materials feedstock.

2. Conclusions

The scientific interest in applying modern technologies such as big data or IoT in the transition to CE is growing. Articles from 2017 and 2018 alone account for 66% of all the publications on the subject to date, reflecting what takes place in practice, given the number of cases and models identified – 60% of all articles mapped. Nevertheless, from the 21 different CE frameworks identified, only three mention IT as a component, and most of them refer to EMF as a primary CE reference, some built on EMF’s ReSOLVE framework. Therefore, IT scientists, scholars and practitioners still do not have at their disposal a framework to be followed that would allow a technological gaps assessment. This framework development was the article’s main purpose, which identified 39 IT capabilities necessary for organisations to consider themselves technologically circular.

The main scientific contribution of this study was the extension of the existing ReSOLVE framework to a level of detail that will allow IT professionals to assess their current CE gaps and plan their actions to enable an easier transition to CE. Additionally, the role modern technologies aligned with Industry 4.0 play in the organisational transition to CE was identified, and the status quo of related research around the world and the most interested institutions and publications were described.

In addition to the traditional literature review of 226 articles retrieved from Scopus® and Web of Science™ databases, the following triangulations were carried out to allow research confirmation and comprehensiveness: content analysis through statistical tool ‘R’, grey literature analysis and expert opinions. The capabilities were then divided according to the six CE principles presented in the literature: six for the design principle, 11 for reduction, 11 for reuse, seven for recycling, one for reclassification and three for renewable energies. The findings indicate that there are principles currently more susceptible to IT than others and that the public administration sector has attracted more research interest in the area possibly because of current initiatives fostered by government entities and agencies.

The following future research opportunities originate directly from this study: the conception of a scale with metrics to allow organisations to self-assess and benchmark (i.e. how many and which capabilities should an organisation implement and to what extent before it can be considered circular); and the confirmation of the framework’s performance by applying it in the form of a questionnaire or survey against selected organisations of different ports and industries.

The limitations of the study lie mainly in the volatility of recent modern technologies that may not have a long lifecycle, making the framework obsolete in the short term. In addition, since it is an essentially theoretical study based on published documentation, it still lacks practical confirmation through organisational case studies.

Acknowledgements

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Appendices

The Appendices are in the Supplementary Information included with the online version of Part I (1).

References


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A novel process for the recovery of platinum group metals (pgms) from ternary alloys using a hydrocarbonyl process is proposed. The hydrocarbonyl process involves treatment of a chloride solution of the pgms with carbon monoxide at ambient pressure. The results demonstrate that the process can provide high purity pgms from a ternary platinum-rhodium-palladium alloy such as that obtained from palladium-nickel catchment alloys used with platinum-rhodium gauzes during high temperature ammonia oxidation.

1. Introduction

Ternary alloys of Pt with Rh and Pd are used for the preparation of catalysts for conversion of ammonia (NH₃). Such ternary alloys also form upon capture of Pt and Rh on catchment alloys of Pd with 5 mass% Ni. Long operation of catalysts made of binary Pt-Rh and ternary Pt-Rh-Pd alloys leads to formation of spent alloys of Pt with Rh and Pd in a broad compositional range. Table I shows compositions of several alloys of this type. Spent ternary alloys of Pt with Rh and Pd require refining for recovery of each precious metal. In most cases, the well-known hydrometallurgical process is applied, which involves dissolution of metals by hydrochlorination. Pt is separated by precipitation of the ammonium salt, ammonium hexachloroplatinate \((\text{NH}_4)_2\text{[PtCl}_6\text{]}\), which is further calcined to obtain sponge Pt. From the filtrate, Pd is extracted in the form \([\text{PdCl}_2(\text{NH}_3)_2]\). In the case of Rh, another method is used, which is known as a nitration process. Rh is precipitated as nitratorhodates of ammonium-sodium from a solution of nitrato complexes. This procedure introduces impurities of various non-ferrous and noble metals; therefore, the products require further purification (1).

JSC R&P Supermetal proposes a new method of refining ternary Pt-Rh-Pd alloys based on hydrocarbonyl processes. The term ‘hydrocarbonyl processes’ implies chemical reactions taking place upon treatment of solutions of pgm chloride complexes by carbon monoxide (CO) at ambient pressure. Hydrocarbonyl processes are based on the high chemical activity of CO molecules in the inner spheres of carbonylchloride complexes. The activity of CO ligands can be demonstrated by the following redox reactions (Equations (i) and (ii)):

\[
\text{CO} + \text{H}_2\text{O} \rightarrow \text{CO}_2 + 2\text{H}^+ + 2\text{e}^- \quad (i)
\]

\[
\text{M}^{n+} + 2\text{e}^- \rightarrow \text{M}^{(n-2)+} \quad (ii)
\]

As a result, the central atom in the complex reduces to the lower (or zero) oxidation state. Pd, gold and silver are reduced to metals, whereas Pt is not reduced.

### Table I: Sample Compositions of Pt-Pd-Rh Alloys

<table>
<thead>
<tr>
<th>Number</th>
<th>Composition, mass%</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pt</td>
</tr>
<tr>
<td>1</td>
<td>84.48</td>
</tr>
<tr>
<td>2</td>
<td>44.20</td>
</tr>
<tr>
<td>3</td>
<td>71.97</td>
</tr>
<tr>
<td>4</td>
<td>21.20</td>
</tr>
</tbody>
</table>

*In ternary alloys formed as a result of capturing platinum group metals on catchment gauze of alloys of palladium and nickel (5 mass%), the sum of iron and non-ferrous metals admixtures can reach 0.1 mass%.
can be either reduced to metal or, at temperature \( T \leq 80^\circ\text{C} \), to polymeric bicarbonyl \([\text{Pt(CO)}]_n\). The reduction proceeds stepwise:
\[
Pd(II) \rightarrow Pd(I) \rightarrow Pd(0) \quad (\text{iii})
\]
\[
Pt(IV) \rightarrow Pt(II) \rightarrow Pt(I) \rightarrow Pt(0) \quad (\text{iv})
\]

Rhodium, ruthenium and iridium are normally reduced to lower oxidation states: Rh(III), Ru(II), Ir(I) and form carbonylchloride anions: \( \text{Rh(CO)}_2\text{Cl}_2^- \), \( \text{Ir(CO)}_2\text{Cl}_2^- \), \( \text{Ru(CO)}_2\text{Cl}_2^- \).

Hydrocarbonyl processes in multicomponent solutions of pgms include a number of reactions running parallel and in series including autocatalytic reactions. In particular, upon treating solutions of chloride complexes of Pt(IV) and Pd(II) by CO the following reactions proceed:

- formation of Pd(II) carbonylchloride (2)
  \[
PdCl_2^{2-} + CO \rightarrow PdCOCl_3^- + Cl^- \quad (v)
\]

- reduction of Pt(IV) to Pt(II) owing to catalytic action of Pd(II) carbonylchloride anion
  \[
  \text{PtCl}_4^{2-} + \text{PdCOCl}_3^- + H_2O \rightarrow \text{PtCl}_4^{2-} + \text{PdCOCl} + CO_2 + 2H^+ + Cl^- \quad (vi)
  \]

- formation of Pt(II) carbonylchloride
  \[
  \text{PtCl}_4^{2-} + CO \rightarrow \text{PtCOCl}_3^- + Cl^- \quad (vii)
  \]

- regeneration of PdCOCl_3^- according to Equation (v)

- reduction of Pt(IV) to Pt(II) owing to catalytic action of Pt(II) carbonylchloride anion (3)
  \[
  \text{PtCl}_4^{2-} + \text{PtCOCl}_3^- + H_2O \rightarrow 2\text{PtCl}_4^{2-} + CO_2 + 2H^+ + Cl^- \quad (viii)
  \]

The Pt(IV) chloride complex in the form of \((\text{NH}_4)_2[\text{PtCl}_6]\) usually contains admixtures of Pd and other metals. It dissolves in the course of the hydrocarbonyl process (Equations (v)–(viii)) by reduction of Pt(IV) to Pt(II):
\[
(\text{NH}_4)_2[\text{PtCl}_6] + CO + H_2O \rightarrow 2\text{NH}_4^+ + \text{PtCl}_4^{2-} + CO_2 + 2\text{HCl} \quad (ix)
\]

Once \((\text{NH}_4)_2[\text{PtCl}_6]\) dissolves, the system remains homogeneous for some time until precipitation of Pd (and Au, if present) starts due to redox decomposition of Pd(II) carbonylchloride, which can be expressed by Equation (x):
\[
PdCOCl_3^- + H_2O \rightarrow Pd + CO_2 + 3Cl^- + 2H^+ \quad (x)
\]

Simultaneously, in the initial period of the \((\text{NH}_4)_2[\text{PtCl}_6]\) reduction, a certain amount of Pt is reduced according to Equation (xi):
\[
\text{PtCl}_4^{2-} + \text{PdCOCl}_3^- + H_2O \rightarrow Pt + \text{PdCl}_4^{2-} + CO_2 + 2H^+ + 3Cl^- \quad (xi)
\]

Accordingly, Pd precipitated by Equations (x) and (xi) typically contains small amounts of Pt.

The Pt(II) chloride complex formed by Equation (ix) transfers to the carbonylchloride anion upon treatment by CO following Equation (vii). It further undergoes inner sphere hydrolysis yielding Pt(0) or bicarbonyl \([\text{Pt(CO)}]_n\) according to Equations (xii) and (xiii):
\[
\text{PtCOCl}_3^- + H_2O \rightarrow \text{Pt} + CO_2 + 2H^+ + 3Cl^- \quad (xii)
\]
\[
\text{PtCOCl}_3^- + 2CO + H_2O \rightarrow \text{Pt(CO)}_2 + CO_2 + 2H^+ + 3Cl^- \quad (xiii)
\]

The kinetics and mechanism of the reaction of CO with solutions of chloride complexes of pgms have been discussed in detail (4–7). In particular, Equation (ix) was studied. \((\text{NH}_4)_2[\text{PtCl}_6]\) was isolated from a solution of chloride complexes upon leaching of industrial concentrate of pgms in the hydrochloric acid + dichlorine (HCl + Cl_2) system and contained 41.45% Pt and 0.65% Pd. Suspension of \((\text{NH}_4)_2[\text{PtCl}_6]\) in water with a solid-to-liquid ratio of 1:11 was treated by CO with vigorous stirring at fixed temperature. After 40 min, \((\text{NH}_4)_2[\text{PtCl}_6]\) dissolved totally forming a cherry red solution with subsequent slow precipitation of black. Afterwards, the black was separated and analysed to assess the Pt:Pd ratio, whereas the filtrate was probed to analyse the content of Pd and then was again treated by CO. The obtained results are presented in Table II.

The data show that the initial precipitate of black contained 25% Pt with respect to the mass of Pd. This can be explained by simultaneously running Equations (x) and (xi). As the content of the Pt(II) chloride complex in solution increases because of transition to carbonylchloride by Equation (vii), the rate of reaction of Equation (xi) decreases. Therefore, the Pd:Pt mass ratio in the precipitate also decreases owing to simultaneous precipitation of Pd and the increase in the rate of Pt precipitation according to Equations (xii) and (xiii) (5). Altogether this leads to complete precipitation of Pd during the initial stages of the process, whereas coprecipitation of Pt is limited to several per cent (Table II).

The results of this experiment showed that a hydrocarbonyl process could be used to obtain Pt from \((\text{NH}_4)_2[\text{PtCl}_6]\) extracted from multicomponent solutions. However, a complete analytical characterisation of the products was
not performed. Therefore, the development of refinery technology for Pt-Rh-Pd alloys was further based on the extraction of Pt from the initial solution in the form of \((\text{NH}_4)_2[\text{PtCl}_6]\) followed by preparation of pure Pt according to the scheme presented in Figure 1.

### 2. Experimental

The analysis of sponge-like metals was performed using a diffraction spectrograph DFS-8 with arc excitation of a spectrum and multichannel analyser of the spectra in the concentration range 0.0003–0.35% and atomic absorption spectrometer novAA® 330 (Analytik Jena, Germany) with flame atomisation for the mass concentration range of 0.01% to 10%. Residual content of Pt, Pd and Rh in solutions was determined by means of atomic absorption spectrometer AAS KVANT.Z with electrothermal atomisation. The detection limit was 0.20 µg l\(^{-1}\) for Pt, 0.05 µg l\(^{-1}\) for Pd and 0.03 µg l\(^{-1}\) for Rh.

To assess the technological possibility of hydrocarbonyl processes for conversion of ternary Pt-Rh-Pd alloys, \((\text{NH}_4)_2[\text{PtCl}_6]\) was extracted from the chloride solution with the following content

<table>
<thead>
<tr>
<th>Number</th>
<th>Treatment conditions</th>
<th>Content in precipitate, (\text{mg (% of extraction)})</th>
<th>Pd:Pt mass ratio in precipitate</th>
<th>Pd in filtrate</th>
<th>Rate of precipitation, % min(^{-1})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1(^b)</td>
<td>90</td>
<td>21.8 (18.79) Pd 5.4 (0.073) Pt</td>
<td>4.00 + 3.76 1.6·10(^{-3})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>95</td>
<td>13.1 (11.29) Pd 7.5 (0.101) Pt</td>
<td>1.75 + 0.75 0.7·10(^{-3})</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>25</td>
<td>62.6 (53.96) Pd 74.9 (1.01) Pt</td>
<td>0.83 + 5.40 0.10</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>25</td>
<td>15.2 (13.10) Pd 232.6 (3.136) Pt</td>
<td>0.07 – 1.31 0.31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5(^c)</td>
<td>90–100</td>
<td>traces</td>
<td>146.4 (1.976) 0.00 – – – –</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^b\) The solid-to-liquid ratio is 1:11. 17.87 g of \((\text{NH}_4)_2[\text{PtCl}_6]\) contains 7.4071 g Pt and 0.1162 g Pd

\(^c\) After 40 min treatment \((\text{NH}_4)_2[\text{PtCl}_6]\) dissolved completely and black started to precipitate

\(^c\) Filtrate after operation number 4 was heated in air to observe formation of \(\text{Pt(CO)}_2\) \(_n\)

---

Table II Results of the Treatment of the \((\text{NH}_4)_2[\text{PtCl}_6]\) Pulp by CO in Water

Fig. 1. Principal technological scheme of hydrocarbonyl process of the Pt-Pd-Rh alloy refinement
of metals: Pt 55.52 g l\(^{-1}\); Pd 21.22 g l\(^{-1}\); and Rh 5.27 g l\(^{-1}\). For the chemical analysis of the product, a weighed portion of the salt was calcined in a muffle furnace at 1000°C. The residual mass of the resulting Pt sponge was 42.94% with respect to the mass of (NH\(_4\))\(_2\)[PtCl\(_6\)] (see Table III).

### 2.1 Extraction of Platinum from Ammonium Hexachloroplatinate

Suspension of 7.50 g of (NH\(_4\))\(_2\)[PtCl\(_6\)] in a 2 M solution of HCl (solid-to-liquid ratio 1:20) was treated by CO at ambient pressure and a temperature of 60°C. Gradual dissolution of (NH\(_4\))\(_2\)[PtCl\(_6\)] was observed with concomitant formation of a red solution of Pt(II) chloride complex according to Equation (ix). After 2.5 h, (NH\(_4\))\(_2\)[PtCl\(_6\)] was dissolved completely and Pt[(CO)\(_2\)]\(_n\) started to precipitate. After 1 h the treatment was stopped and the resulting solution was enclosed in a CO atmosphere for precipitation coagulation. After cleaning the solution, the precipitate was filtered off, washed with 2 M HCl and calcined in a muffle furnace at 1000°C. 277.44 mg of Pt sponge was obtained (Precipitate I).

Filtrate from Precipitate I together with the scourge was treated with CO at 40°C. After 30 min, platinum carbonyl [Pt(CO)\(_2\)]\(_n\) started to form (Precipitate II). After 3 h, the gas treatment was stopped and the reactor was closed in a CO atmosphere for coagulation of Precipitate II. The solution was decanted and Precipitate II was suspended in 2 M HCl and then filtered off under vacuum and washed with 2 M HCl on a filter. Precipitate II was dried and calcined at 1000°C, which yielded 2289.12 mg of Pt sponge. Compositions of Precipitates I and II are given in Table IV, while Table V shows the distribution of the elements for these precipitates.

### Table III Composition of the Pt Sponge After Calcination of (NH\(_4\))\(_2\)[PtCl\(_6\)] at 1000°C

<table>
<thead>
<tr>
<th>Element</th>
<th>Content, mass%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Platinum</td>
<td>98.5073</td>
</tr>
<tr>
<td>Rhodium</td>
<td>1.037</td>
</tr>
<tr>
<td>Palladium</td>
<td>0.3598</td>
</tr>
<tr>
<td>Gold</td>
<td>0.0188</td>
</tr>
<tr>
<td>Copper</td>
<td>0.0043</td>
</tr>
<tr>
<td>Iron</td>
<td>0.0025</td>
</tr>
<tr>
<td>Nickel</td>
<td>0.0066</td>
</tr>
<tr>
<td>Zinc</td>
<td>0.0061</td>
</tr>
<tr>
<td>Lead</td>
<td>0.0161</td>
</tr>
<tr>
<td>Magnesium</td>
<td>&lt;0.0005</td>
</tr>
</tbody>
</table>

### Table IV Composition of Precipitates Obtained by Carbonylation of (NH\(_4\))\(_2\)[PtCl\(_6\)]

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition, mass%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitate I</td>
<td>Precipitate II</td>
</tr>
<tr>
<td>Platinum</td>
<td>95.7156</td>
</tr>
<tr>
<td>Rhodium</td>
<td>0.3000</td>
</tr>
<tr>
<td>Palladium</td>
<td>2.8000</td>
</tr>
<tr>
<td>Gold</td>
<td>0.1250</td>
</tr>
<tr>
<td>Copper</td>
<td>0.1850</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Element</th>
<th>Composition, mass%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Precipitate I</td>
<td>Precipitate II</td>
</tr>
<tr>
<td>Platinum</td>
<td>99.7100</td>
</tr>
<tr>
<td>Rhodium</td>
<td>0.2100</td>
</tr>
<tr>
<td>Palladium</td>
<td>0.0150</td>
</tr>
<tr>
<td>Gold</td>
<td>&lt;0.0003</td>
</tr>
<tr>
<td>Copper</td>
<td>0.0080</td>
</tr>
</tbody>
</table>

### Table V Distribution of the Admixtures Over Precipitates I and II

<table>
<thead>
<tr>
<th>Sum of admixtures, mass%</th>
<th>Precipitate I</th>
<th>Precipitate II</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Sigma_1)</td>
<td>0.745</td>
<td>0.038</td>
</tr>
<tr>
<td>(\Sigma_2)</td>
<td>0.068</td>
<td>0.007</td>
</tr>
<tr>
<td>(\Sigma_3)</td>
<td>3.475</td>
<td>0.245</td>
</tr>
<tr>
<td>(\Sigma_{1, 2})</td>
<td>0.813</td>
<td>0.045</td>
</tr>
<tr>
<td>(\Sigma_{1, 2, 3})</td>
<td>4.288</td>
<td>0.290</td>
</tr>
<tr>
<td>Pt, %</td>
<td>95.712</td>
<td>99.710</td>
</tr>
<tr>
<td>(\Sigma_{Pt, Rh, %})</td>
<td>96.012</td>
<td>99.920</td>
</tr>
</tbody>
</table>

\(\Sigma_1\) = sum of heavy non-ferrous metals (Cu, Ni, Fe, Pb, Zn, Sn, Cd); \(\Sigma_2\) = sum of light non-ferrous metals (Ca, Mg, Al); \(\Sigma_3\) = sum of noble metals (Pd, Rh, Au, Ag)
2.2 Extraction of Palladium from the Filtrate After Deposition of Ammonium Hexachloroplatinate

After sedimentation and filtration of \((\text{NH}_4)_2[\text{PtCl}_6]\), the solution contains chloride complexes of Pd(II) and Rh(III) together with residual Pt(IV), which was determined by a solubility equilibrium of \((\text{NH}_4)_2[\text{PtCl}_6]\) and concentration of \(\text{NH}_4\text{Cl}\). For extraction of Pd, the filtrate was treated by CO at ambient pressure and a T of 50–70°C. Blackening of the solution was noticeable in 2–3 min. After 3 h 15 min of treatment, the reactor was closed under CO atmosphere for coagulation of Pd black. The solution was decanted and the precipitate was suspended in 2 M HCl, filtered off and washed on a filter with 2 M HCl, after which the filtrate was closed in a flask under CO atmosphere.

2.3 Extraction of Rhodium After Precipitation of Palladium

After extraction of Pd the remaining filtrate has yellowish-green colour, a characteristic of Rh(I) \((\text{Rh(CO)}_3\text{Cl}_2^-)\), which is stable only in highly acidic media and decomposes in basic media. Consequently, upon adding alkali to the solution of Rh(I) carbonyl chloride, blackening was observed. Heating the pulp led to coagulation and sedimentation of Rh black. The precipitate was filtered, suspended in 2 M HCl and filtered again. The obtained Rh black easily dissolved in the HCl + hydrogen peroxide \((\text{H}_2\text{O}_2)\) mixture with formation of a pink solution typical for \(\text{H}_3\text{RhCl}_6\). The analysis of the filtrate showed that it did not contain Pt, Pd or Rh.

3. Discussion of the Results

The results of extraction of Pt from the \((\text{NH}_4)_2[\text{PtCl}_6]\) pulp by treating with CO were analysed. The content of Pt in Precipitates I and II amounted to 95.712% and 99.710%, whereas the rates of extraction for \((\text{NH}_4)_2[\text{PtCl}_6]\) were 8.37% and 90.81%, respectively. The analysis of the filtrate showed that the total extraction of Pt into Precipitates I and II was equal to 99.96%. The content of heavy non-ferrous metals \((\Sigma_1)\) in Precipitate II was more than an order of magnitude less than in Precipitate I, whereas the content of light non-ferrous elements \((\Sigma_2)\) in Precipitate II was almost one order of magnitude less than in Precipitate I. The content of noble metals in Precipitates I and II \((\Sigma_3)\) showed a 14 times decrease owing to extraction of sizable amounts of Au, Ag and Pd into Precipitate I. At the same time, the content of Rh in Precipitates I and II was 0.30% and 0.20%, respectively, meaning that Rh remains the principal admixing element; the combined content of Pt and Rh \((\Sigma_{\text{Pt, Rh}})\) in Precipitates I and II amounted to 96.012% and 99.920%, respectively. This appears to be due to accumulation of Rh in solution in the form of Rh(I) carbonylchloride \((\text{Rh(CO)}_2\text{Cl}_2^-)\) and its adsorption of Pt carbonyl. Complete removal of Rh is possible by oxidative washing of the precipitate due to formation of Rh(III) chloride complex. In particular, suspending Precipitate II in 2 M HCl in air leads to pink colour of the filtrate, indicating the presence of \(\text{H}_3\text{RhCl}_6\). Also, one can speculate that higher content of non-ferrous metals in Precipitate I might be a consequence of insufficient washing.

4. Conclusion

The performed study has shown that hydrocarbonyl processes can be used for the individual recovery of precious metals from ternary Pt-Rh-Pd alloys. It is also shown that the hydrocarbonyl process can be used for conversion of \((\text{NH}_4)_2[\text{PtCl}_6]\) into pure Pt, which can be exploited for production of Pt from technogenic and natural products. It should be stressed that hydrocarbonyl processes have vast potential in technology and application of pgms and can be used for concentrating as \(\Sigma_{\text{Pt, Pd, Au, Ag, Si, Te}}\) or \(\Sigma_{\text{Rh, Ru, Ir}}\) from multicomponent industrial products based on non-ferrous metals (6–9); upon refining concentrates and various alloys (10, 11); and in manufacturing powders of pgms with desired physicochemical properties and deposited catalysts, including those for neutralisation of exhaust gases of combustion engines (12).

It is expected that further investigation of the processes of hydrocarbonylation of pgm chloride complexes will lead to preparation of new composite materials containing one or more pgms together with carbon in either form (13).

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Introduction

The CE is an economic system used to transform the traditional linear economy and it has been considered as a potential enabler of sustainable development (1). In a linear economic system, raw materials are extracted, manufactured, used and then discarded; such an end-of-life process leads to environmental degradation due to the continued exploitation of limited resources (2). CE can be defined as "an industrial system that is restorative or regenerative by intention and design" (3). It replaces the end-of-life concept with restoration, taking products and material use from ‘cradle to grave’ to ‘cradle to cradle’ (3, 4). That is, CE considers discarded products or components as materials and resources for the input of new production processes. For manufacturing industries facing challenges of resource scarcity and environmental impact, it is important to reduce, reuse and recover resources in production and consumption processes and keep products and materials at their highest utility and value (5, 6). In order to do so, manufacturing industries require their business models, products and supportive networks to be redesigned to fulfill circular solutions (7). CE thereby creates an opportunity for business innovation which is aimed at value creation, cost reduction, revenue generation and resilience enhancement (8).

CE is not a brand-new idea for sustainability issues. The original concept emerged from the 1960s with the awareness of limited resources and coexistence of economic and environmental systems (2). It gradually matured with the development of cleaner production, the performance economy, product service systems (PSS) and regenerative design. Cleaner production is a corporate initiative applied to reduce the impact of products and...
production by eliminating harmful materials and emissions (9). The performance economy serves to create wealth with less resource consumption via selling performance (for example, results and utilisation), instead of selling goods (10). PSS combines marketable products and services to satisfy customer needs while extending the product life cycle (11). Regenerative design regards production as a resilient ecosystem, where energy and materials can be replaced and reused continuously (12). The above concepts have been incorporated into managerial practices and principles for CE and form sustainability visions for companies (2, 8). In addition, for the past 10 years, CE has received more attention regarding how companies associate it with business model innovation and create environmental and social value (13).

Although manufacturing industries might focus more on the production aspect of circularity, the core of CE is not merely about how companies produce and recycle eco-friendly products. It actually goes beyond single product and service design and requires changes to the whole production process and consumption behaviour, including consumer awareness, network-centric operational logic, community integration and even governmental interventions (13–15). Since this complicated process involves multiple actors and strategic plans at the micro level (for example, circular products and business models) as well as the macro level (policies and regulations) (16), any improper decision might lead to failure. Many studies have discussed the advantages and challenges of CE, but few of them indicate that some misconceptions about circular manufacturing can guide companies to unsustainable performance. Based on the exploration of business cases, this article clarifies crucial aspects that influence the design of business models and sustainability, provides a holistic context and considerations for resolving these conflicts and discusses the implications and managerial practices for companies that intend to develop circular business models.

Circular Business Models and Strategies

CE contains multiple elements such as resource recovery, energy conservation, product life extension and recycling. These elements should be associated with revenue streams to help companies develop their business models. Companies also need to clarify how they create, deliver and capture value within closed material loops (1, 17, 18). Below we review and summarise important CE business models and their strategies from industry research reports and academic studies.

Accenture, Ireland, (19) has analysed 120 case studies and proposed five circular business models in its report. These models are (a) circular supplies, (b) resource recovery, (c) product life extension, (d) sharing platforms and (e) product as a service. The circular supplies model means that companies earn revenues via supplying renewable, recyclable or biodegradable resources in place of disposable and virgin materials. The resource recovery model reprocesses disposed products and turns them into new or available products or energy. Such a model often transforms waste into value through recycling or upcycling services. In the product life extension model, companies reduce production costs of new products via repairing, upgrading or remanufacturing. The sharing platform model makes possible shared access to products. It decreases the product ownership rate and encourages users to share products such as vehicles and accommodation. As for the product as a service model, companies provide leasing or renting services, where customers pay only for the product use instead of buying the whole product (19).

Transition from linear 2 circular (R2π) is a three-year research project beginning in 2016. It explores markets and policies of CE and shows how circular business models can be implemented. By analysing cases in electronics, food, plastic, textile and water sectors across European countries, this project has identified seven patterns of circular business models, including (a) circular sourcing, (b) resource recovery, (c) reconditioning, (d) remaking, (e) access, (f) performance and (g) coproduct recovery (20). The first six patterns are similar to the five models in Accenture’s report while the coproduct recovery pattern implicates another way to run a circular business. This pattern creates a new industrial value chain, where residual outputs or byproducts of a company can become feedstock or inputs for another company. For example, fly-ash from coal combustion can be used as clinker for producing cement. Such a pattern usually works via co-located facilities since proximity can save transport costs and reduce energy use (20). In other words, industrial symbiosis can be applied to enhance circular production. The Kalundborg Symbiosis is a well-known example that integrates nearly 20 different byproduct exchanges to create ecological benefits (21).
Table I Circular Business Models and Their Strategies

<table>
<thead>
<tr>
<th>Reference</th>
<th>Resource supplies</th>
<th>Resource recovery</th>
<th>Product-service systems</th>
<th>Open innovation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Accenture (19)</td>
<td>Circular supplies</td>
<td>Resource recovery</td>
<td>Product life extension, Sharing</td>
<td>–</td>
</tr>
<tr>
<td>R2n (20)</td>
<td>Circular sourcing</td>
<td>Resource recovery</td>
<td>Re-condition, Access, Performance</td>
<td>Co-product recovery, –</td>
</tr>
<tr>
<td>Pieroni et al. (13)</td>
<td>–</td>
<td>–</td>
<td>Access, Performance</td>
<td>Industrial symbiosis, Alternative ownership</td>
</tr>
</tbody>
</table>

By reviewing 94 academic papers, Pieroni et al. (13) identify three archetypes of CE-oriented business model innovation, including (a) access, (b) performance and (c) industrial symbiosis. These archetypes require elements such as reverse logistics, take-back systems, incentives and service-oriented revenue schemes to fulfill the circular supply chain. In addition to the emphasis on business sectors and environmental value, Pieroni et al. (13) also present an archetype dedicated to social sustainability, namely alternative ownership: cooperatives and collectives. This archetype focuses on integration with local communities, partnerships with non-governmental organisations (NGOs) and employee ownership. Although this model is not purely profit-oriented, it does facilitate CE. For example, Globechain, a British product reuse platform, enables corporations and users to donate their unwanted equipment and materials to charities or social enterprises via its data technology, thus extending the product longevity. Jégou and Manzini (22) also show how an interactive community encourages residents to share resources and create mutual assistance.

Based on the above discussions, Table I summarises four categories of circular business models, including resource supplies, resource recovery, PSS and open innovation. Resource supplies and resource recovery focus on how companies replace virgin raw materials with renewable resources and turn them into the input of circular production. These models require the technology to help companies collect and extract available resources from recycled materials. PSS is a concept of multiple models, including product-oriented PSS, use-oriented PSS and result-oriented PSS. Products play a central role in product-oriented PSS and use-oriented PSS; these models extend product longevity by providing maintenance, sharing or leasing services (11). Result-oriented PSS is based on the idea of a performance economy, where ‘ownership-based’ business models are replaced with ‘pay-per-use’ models to reduce production and fulfill CE requirements (8, 23). As for open innovation, it encourages companies to work with different sectors or communities to expand their vision and resources. Knowledge and information sharing is the key to successful collaboration (14).

The above categories of business models show how companies or manufacturers can engage in circular production. To further clarify how they create and capture value, it is important to look at managerial practices. Through extensive studies of value creation in CE, Ünal et al. (18) have summarised six guiding principles for addressing managerial practices in circular business models, including (a) energy efficiency driven practices, (b) environmentally-friendly material usage-driven practices, (c) ‘design for X’ (DfX) practices (for instance, design for recycling, design for remanufacturing and reuse and design for disassembly), (d) support of all partners to develop awareness and new skills, (e) establishment of effective communication with stakeholders and (f) managerial commitment. Figure 1 connects the proposed business model categories with the managerial practices and business strategies. The resource supplies and recovery models indicate ‘what’ resources (i.e., renewable, eco-friendly and biological materials and energy) should be utilised and restored in production processes. The PSS model implicates ‘how’ companies and designers elevate the design of circular products and interact with customers via service offerings. The open innovation model implies ‘who’ companies or manufacturers should work with to develop a new alliance and novel ideas and skills. Managerial commitment is the most important prerequisite that influences the attitudes and decisions of all stakeholders and actors in the business model (8).

In summary, the above strategies and practices help define the role, resources and value network of companies and stakeholders; they also provide basic guidance and direction for designing circular business models in the early design phase.
Barriers to Circular Business Models

New technology and processes for resource renewal can help improve circular production. However, how managerial commitment changes stakeholders’ and customers’ thinking and behaviour is actually the key to CE. As CE involves many complex elements and value networks, multiple challenges and barriers will emerge when designing circular business models.

Figure 2 presents both the inside and outside barriers to circular business models. By interviewing 153 business leaders and 55 government officials in Europe, Kirchherr et al. (15) classified CE barriers into four categories, including cultural, regulatory, market and technological barriers. Major cultural barriers are lacking consumer interest and awareness and a hesitant company culture. The circular system will not be closed if customers lack environmental concerns and are irresponsible about returning materials and components back to the cycle when products are no longer in use (8, 24). As shown in Figure 2, low consumer awareness and a lack of proper take-back systems will generate difficulties in material identification and separation, ensuring purity, distribution and transportation, which are great challenges for resource recovery (25). Furthermore, circular business models sometimes require radical innovation that accompanies investment risks (26). For example, since bio-based plastics are more expensive than fossil fuel based plastics, suppliers might fear for investments in providing circular resources (15). Even though the resources are available to support biological and technical cycles, companies still need more DfX practices and facilities to ensure the optimisation of material flows and keep the flexibility and upgradability of circular products (16).

CE has been considered as an enabler of sustainability. In turn, sustainability should not only address resource recovery and eco-economic decoupling but also deal with social issues such as safety, labour rights and community empowerment. Kirchherr et al. (5) reviewed 114 definitions of CE and found that only 13% of definitions referred to the holistic concerns of sustainability (i.e. considerations of economic, environmental and social dimensions). CE seems relatively silent on the social dimension (27). For example, the recycling of hazardous electronic waste (e-waste) should be carefully managed, but untrained workers in India carried out dangerous procedures without protective equipment and thus resulted in occupational health hazards (28). As many companies today have claimed to promote corporate social responsibility (CSR), social concerns should be incorporated into their business strategies. Therefore, the conflict between economic growth, labour rights and health is a serious issue that companies must address. For manufacturing companies, it is important to find new partnerships for building innovative and collaborative business models (6). Open innovation such as industrial symbiosis or alternative ownership lets multiple companies or partners share resources and information, but the protection of intellectual property rights and sensitive information might become a problem (29).
In addition to the above challenges inside the business model, regulatory barriers such as obstruction of laws and regulations and limited circular procurement could also obstruct circular manufacturing in some cases (15). Therefore, synergistic governmental interventions including incentives, regulations and penalties could be potential drivers that improve companies’ and stakeholders’ attitudes and behaviour.

As shown in Figure 2, most barriers have mutual influence on each other and they refer not only to firms but also to their suppliers, stakeholders, customers and even the government. To deal with these barriers, design and systems thinking with collaborative networks should be built to generate appropriate circular business models.

Improving Circular Business Models

Although CE is aimed at reducing waste and keeping materials at their highest utility, it is not always guaranteed to produce sustainable solutions. Pieroni et al. (13) have indicated that not all CE-oriented business models can accommodate sustainable principles. Below we point out three ways in which the misconception of circular manufacturing could lead to environmental degradation. These include improper or incomplete considerations of (a) the use of biodegradable materials, (b) modular design for product life extension and (c) upcycling for new production processes. These issues are respectively associated with the three business models discussed previously, namely resource supplies, PSS and resource recovery. The three models here represent different phases of circularity, including input, use and return of resources.

Circular supplies use materials extracted from discarded products or renewable or bio-based resources that can be returned to the natural environment (20). Generally, biodegradable materials are considered to be more environmentally friendly. However, the question remains uncertain when it comes to the life cycle assessment (LCA). For example, more and more companies have promoted the marketing of biodegradable shoes. Unfortunately, biodegradable materials actually make soles fragile.
and have a limited time for storage since they can be decomposed by oxygen and water; the broken shoes also cannot be repaired (30). Consequently, the average life cycle of biodegradable shoes is far shorter than traditional shoes, especially for island countries which are usually hotter and wetter. Customers thus purchase more products and create more production waste. Another example is biodegradable drinking straws used to replace disposable plastic straws. Biodegradable straws are often composed of paper or bio-based polylactic acid (PLA). However, paper straws consume more wood and water resources while PLA straws require a specific temperature and humidity to be decomposed. For countries that do not have available facilities to recycle PLA, PLA products will be treated as general waste and result in linear production (31). The above cases demonstrate that the effect of circular sourcing depends on policies and conditions of countries and regions. Figure 3 shows that using bio-based or recyclable materials without considering the duration of products in social, geographical and institutional contexts might shorten the overall product life cycle and increase production or consumption waste, energy use and investment costs.

The second misconception occurs in DFX practices for circular products. When it comes to design for disassembly, modular design is regarded as the gateway to product life extension because easy disassembly makes products maintainable, repairable and upgradable on a modular basis (32). Proper modular design can be beneficial for recycling. However, according to Schischke et al. (33), modular product design does not necessarily meet the sustainable requirements since it needs more material consumption for producing multiple modules (see Figure 4). In addition, to take modular smartphones as an example, users might replace broken modules with new ones to extend the lifetime of devices, but they might also upgrade replaceable modules more frequently to keep pace with new technology features (33). In other words, modular design principles seem to resolve repairing and recycling issues, but the results still depend on consumption behaviour. Furthermore, product life extension requires service offerings for maintenance or recycling. Technical problems such as lacking repair shops or inconvenient services will decrease users’ willingness to deal with their products. On the other hand, for electronic products phased out rapidly, some modules might be no longer available when customers need replacement. Accordingly, the design of circular products should consider not only the product flexibility but also collaborative consumption and supportive services that encourage customers to bring used products back to the cycle (34). Furthermore, product and process optimisation for resource efficiency is required to ensure the reduction of energy and material use, and it can be fulfilled by applying resource efficiency measures (REM) and redesigning manufacturing processes (16).

In summary, the considerations of modular design should go beyond pure product innovation; they involve service strategies, customer behaviour and the attributes and conditions of the industry. The third misconception involves upcycling. Upcycling makes use of discarded products or materials and transforms them into new products of higher value (35). Although this concept sounds promising, the definition of ‘higher value’ could be doubtful. Turning recycled plastic bottles into fashion clothes is a common example of upcycling. However, the high value of clothes comes from their design and brands, instead of the processed polyester. These bottles are still single-use plastics. The processed polyester does not return to the
cycle of bottle manufacturing to decrease the use of fossil-based materials. It seems that the food and beverage industry passes a recycling problem on to the textile and fashion industry; it encourages guilt-free consumption since customers regard these clothes as a sustainable solution (36). Starting marketing campaigns based on circularity and sustainability thinking is important for promoting products and raising customers’ environmental and ethical awareness (1). However, such a misconception runs the risk of actually opening the production cycle and leading to more consumerist lifestyles (Figure 5). At the moment, rethinking whether discarded products can better return to their original production processes and close the material loop is a top priority of resource recovery. For upcycling, the best situation is to derive resources from waste or byproduct streams of original products and turn them into new and practical products.

A New Framework for Circularity

Figure 6 presents a framework to summarise important considerations for resolving the above mentioned concerns. Although resource supplies, product life extension and resource recovery are related to different business models as well as different phases of product life cycle, these considerations are interconnected. For example, resource supplies have gone beyond the application of bio-based materials. They should consider whether the materials can actually help improve product life extension. Likewise, modular design approaches should emphasise more than just product life extension. Companies should develop comprehensive service systems to manage recycled modular products, byproducts and waste materials for resource recovery or further upcycling processes. These considerations are in accordance with the four main principles of circular products proposed by Urbinati et al. (16): (a) energy efficiency and usage of renewable sources of energy, (b) product and process optimisation for resource efficiency, (c) product design for circularity and (d) exploitation of waste as a resource. Moreover, all these considerations should be addressed simultaneously to ensure holistic systems thinking of circular business models.

On the other hand, the centre of Figure 6 implies that circularity thinking should take social responsibility into account. Reducing material and energy use brings immediate economic benefits for companies, but how business models can contribute to social issues or how companies receive feedback or benefits by dealing with social concerns remains uncertain (2). Actually,
incorporating CSR strategies into product-service offerings brings advantages beyond product sales. For example, participatory activities such as creative workshops or living laboratories encourage customers and the community to share their resources, lifestyles and experience of using products; these activities not only foster community empowerment but also provide companies first-hand information for improving their products and services (37). Furthermore, taking care of workers’ and consumers’ health and safety in any phases of product life cycle will create positive brand image for companies.

**Opportunities for Circular Business Models Innovation**

According to the framework presented in Figure 6, product life extension is the key to reducing rapid and excessive consumption for PSS and DFX practices; it is also a main purpose of resource supplies since circular manufacturing requires not just using natural and recyclable materials but also creating durable products to slow material and energy flows. For companies and stakeholders, it is important to create and capture value via extending product lifetime in their business models. Product life extension can be twofold: technological and operational. The technological aspect means exploring renewable and durable materials and using them to increase product longevity. The operational aspect implicates how companies influence product use, disposal and recycling through operational strategies. Developing supportive service offerings will aid companies in creating business opportunities. Strategies such as leasing, renting and pay-per-service have been presented in Figure 1. These strategies help manufacturers and product owners handle the whole life cycle of products and decide when they should be repaired, recycled or remanufactured. Companies such as Philips, The Netherlands, and Xerox, USA, have turned product-centric policies into solution-based schemes by providing their users rental and maintenance services in the business-to-business (B2B) model. The second-hand scheme has also received increasing attention in recent years. Companies such as LENA, The Netherlands, and Patagonia, USA, apply the ideas of fashion library and clothing recycling to rent, supply or exchange second-hand clothing to extend product longevity and decrease the use of raw materials.

It is clear that selling products is no longer a major way to earn revenues in circular business models. Manufacturing industries must rethink their strategies to reduce the environmental impact while opening new revenue streams (38). New business models with radical innovation and transition can be found in the performance economy, where companies sell information, knowledge and experiences in place of tangible products. DuPont de Nemours, USA, is an example transforming its business from chemistry manufacturer to safety management provider by offering biology and knowledge-intensive solutions (10). Here,
information and communication technology (ICT) has become an important tool to support the interaction, management and monitoring systems of products and services (6).

On the other hand, open innovation based on the support and effective communication of all partners will boost business opportunities too. For instance, the Dell Reconnect program (Dell, USA) works with Goodwill Industries, USA, providing over 2000 sites in North America for recycling e-waste. The recycled e-waste is then transported to Wistron GreenTech, Texas, USA, to extract metals and sort plastic components for further processing (39). In addition to the industry alliance, working with customers intensively also helps create environmental and economic value. The concept of customer-to-manufactory (C2M) aids companies in designing products with their customers and building customisable intelligent manufacturing systems (40). Because companies provide customers with personalised products, they avoid producing useless functionality and components and thus save unnecessary resource waste. In addition, with the assistance of industrial internet of things (IIoT) and big data technology, companies can carry out online monitoring for products’ health diagnosis and maintenance services (40). That is, understanding customers’ personalised needs can help improve resource efficiency.

As discussed previously, managerial commitment is the backbone of circular business models which influences circular-oriented policies, objectives and awareness (18). To raise managerial commitment, cooperative initiatives such as CSR and global reporting initiatives are applied to change corporate culture and stakeholder attitudes (41). In addition, incorporating artistic thinking into corporate culture at the managerial level can promote behaviour change and environmental and social awareness and even extend the product life cycle (42). Support from governments such as incentives or proper tax policy is equally important to transform company and customer behaviour (15, 16). For instance, the Norwegian government levies environmental taxes on plastic producers and importers, but the taxes will be cut if companies recycle enough plastic bottles. Customers also pay a ‘mortgage’ for buying bottled products; only when they throw the used bottles into the ‘mortgage machines’ in supermarkets can they retrieve their money (43).

In summary, collaborative networks for open innovation should be built to increase the interaction between stakeholders for circulating resource use. Effective communication and management systems based on well-designed ICT are necessary for developing PSS solutions that reduce production costs and improve resource efficiency.

Conclusions

Circular business models encompass multiple concepts and approaches such as cleaner production, eco-efficiency, the performance economy and PSS; they involve various actors including suppliers, manufactures, customers and even the government. For such a complex system, any misconceptions or improper decisions shortening the product life cycle or expanding consumer demands will cause environmental degradation and unsustainable consumption.

To fulfil the goals and principles of CE, it is important to clarify the holistic context of sustainability, including the impact and value of economic, environmental and social dimensions. Systems thinking should be established to deal with the design of circular business models and the considerations should be addressed at both the micro level and the macro level. At the micro level, companies should conduct LCA and choose renewable and recyclable resources wisely based on product life extension. Renewing waste and byproducts and turning them into new and practical products are also important for resource recovery. In addition, comprehensive service offerings should be developed to reduce consumerism, support recycling mechanisms and extend product longevity. At the macro level, working with governments and different sectors, making good use of incentives and engaging in cooperative initiatives are needed to change production and consumption patterns as well as behaviour and attitudes towards circular lifestyles.

Because CE involves changes in the supply chain, stakeholder networks and product-service offerings, it could be a long-range undertaking. Improving CE business models based on systems thinking will guide policy makers to handling their goals and tasks properly. Only by reconciling short-term goals inside the business models with long-term goals outside the models can companies innovate in line with CE trends.

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The circular economy (CE) is an important approach and current trend in environmental sustainability. The implementation of the CE depends on the adoption of sustainable practices from the planning stages of new product development (NPD). Although the literature recognises the need to apply CE practices into NPD, few studies have tried to provide support for the issues based on real case studies. This article aims to identify and analyse practices, barriers and drivers to the development of circular products. To achieve this objective, a multiple case study was carried out in three medium and large Brazilian companies that have environmental concerns and, at the same time, are continuously involved in NPD activities. The results show that the companies’ circular product designs already foresee waste and recycled components as raw materials. In addition, it was found that infrastructural aspects and low awareness of customers regarding sustainability are challenges to overcome. Finally, for the adoption of CE practices, regulatory legislation stood out as a significant driver. This article contributes to theory and practice by providing empirical evidence of how companies have planned to build circular products by incorporating circular practices into the NPD process.

1. Introduction

Concern over scarce resources, environmental preservation and global warming has grown among consumers and influenced governments to introduce tougher regulations for companies to make them rethink the environmental impact of their activities (1–2). Consumers and society have raised the demand for and are paying more attention to green products (3). The need to shift the linear production system to a more sustainable and circular model has been recognised for some years by international organisations (4, 5) and is discussed in current research on sustainability (1, 6).

The trend towards adoption of the CE has also demanded changes in consumption patterns favouring more environmentally sustainable products and services (7). These changes imply the adoption of concepts such as dematerialisation (8) and the sharing of products and services (9, 10). In order to move towards a more circular
approach – from cradle to cradle – slowing the consumption of natural resources, the CE theory has proposed the recirculation of material resources from the planning stage of NPD (11, 12). However, it is known that traditional and green NPD approaches are different (13).

NPD under the CE perspective is aimed at the usage of biodegradable materials and renewable energy and the sharing of products and services (2). The development of new, more energy efficient technologies, equipment, installations and use of the internet and information technology can improve utilisation of resources and prevent pollution (14). The adoption and development of new technologies integrated with products (as such, the internet of things) have allowed the creation of new innovative business models (15, 16).

Since the integration of CE into NPD is one of the most prominent areas in operations management (13, 17) and facing the need to better understand management practices that drive this integration, this article aims to identify and analyse the practices, barriers and drivers of CE integration in NPD. For this, we have carried out a qualitative, multi-case study in three large- and medium-sized Brazilian companies that have environmental concerns and are at the same time continuously involved in NPD activities.

It is important to point out some definitions before proceeding. First, examples of practices analysed in the article are the use of production waste, remanufacturing, reuse, recycling, reverse logistics and environmental assessment. Second, drivers are motivational factors that lead organisations to adopt CE in NPD, such as consumer demand and legislation. Third, barriers are factors that hamper the adoption of some of the practices related to CE, for example, need for high investment in technologies and low demand for products made by remanufacturing or with recycled components.

After this introduction, Section 2 presents the theoretical framework on the development of products in the context of a CE. Section 3 presents the activities regarding the research method. In Section 4, the results will be shown. Finally, Section 5 discusses the results in comparison with the literature and outlines this study’s conclusions.

2. Circular Product Design

CE is one of the main trends currently considered by academics and practitioners around the world in environmental sustainability (1, 5). The relevance of the CE is that it presents solutions to the challenges of waste generation, resource shortages and carbon dioxide emissions, as well as the potential to offer economic, environmental and innovation benefits (6). According to Kirchherr et al. (18), the CE can be defined as an economic system that replaces the concept of ‘end-of-life’ by ‘cradle to cradle’ using the reduction, reuse, recycling and recovery of materials in production, distribution and consumption processes. Kjaer et al. (19) argue that the CE’s main objective is to keep the value of products, materials and resources in the economy for as long as possible. In addition, due to reduced consumption of resources, a CE can also improve economic performance (19).

The Ellen MacArthur Foundation, UK, proposed the ReSOLVE model for the adoption of the CE (5). Some studies have highlighted the importance of the ReSOLVE model to a CE (2, 16). In summary, the principles are: (a) regenerate: aims at restoring the health of the environment by proposing the use of energy and renewable materials; (b) share: maximum use of the product by its sharing among users; (c) optimise: aims to increase the performance of the product, removing waste in the production and supply chain; (d) loop: aims to keep components and materials in closed loops; (e) virtualise: deals with the development of digital solutions to reduce the production cycle and its environmental impacts; and (f) exchange: replaces old materials from non-renewable technologies by applying new technologies.

Several factors have motivated and driven the adoption of CE practices (2, 7, 20, 21). Jesus and Mendonça (20) define three different categories: technical stimulus; economic and market factors; institutional, regulatory and social motivations. Technical stimulus comprises the technological availability that facilitates the optimisation of resources, remanufacturing and the development of sharing solutions. Institutional, regulatory and social motivations are associated with increasing environmental concern and connected to the social demand for the protection of the environment and changes in consumer preferences.

Among the drivers for the adoption of CE practices, Govindan and Hasanagic (21) pointed out regulatory aspects which promote cleaner production, such as the recent concern on climate change and global warming, the demand for renewable energy and the increased value of products that are designed to last longer, among others. However, transitioning from a linear to a CE is not trivial and several studies have pointed out barriers that must be acknowledged (20–23). Some
factors that stand out as relevant and that should be considered in this transition are technological aspects (technological immaturity, for example), market and economic factors (high investments and uncertainty of returns) and institutional and regulatory challenges (lack of legislation to regulate or stimulate the adoption of CE) (20).

Bressanelli et al. (24) identified the following challenges that may hinder CE adoption: economic and financial viability, market, product characteristics, standards and regulation, supply chain management, technology and consumer behaviour. The risk of product development and production that is unattractive to customers, the longer return on investment, especially in cases where companies are proposing servitisation and the few legal incentives can be barriers to CE adoption (24).

In classifying barriers to CE adoption, Govidan and Hasanagic (21) proposed eight clusters: government, economic, technological, knowledge and skill, management (for example, top management support), culture and social, market and other solutions. Govidan and Hasanagic (21) also highlighted aspects such as ineffective CE legislation and high costs associated with recycled material as market barriers towards the CE.

The effective adoption of a CE depends fundamentally on practices associated with NPD (11). However, the NPD process in the CE context is strictly different from conventional NPD (13), because in CE the economic and environmental values of products are preserved as long as possible, either by extending the product’s useful life or by creating the possibility of reusing it (25). Among these characteristics of circularity in the NPD process, it is observed that decisions must envisage, from the planning stage of the project, the use of the principles of material circulation and energy reduction (26), regeneration (5) and the preservation of materials for as long as possible (27).

The adoption of these principles aims, overall, to keep the products in the economic system, so as to avoid as much as possible the extraction of virgin raw material from nature (28, 29). In addition, as observed by Hollander et al. (25), the economic and environmental value of products developed under the principles of the CE should be designed for maximum preservation to prolong their life cycle or return the products and their components to the market. Thus, it is essential that the principles of regeneration, sharing, optimisation, recycling, remanufacturing, virtualisation and the substitution of toxic and non-renewable materials for non-toxic and renewable ones should be regarded in NPD (2).

A circular product should also be attentive to product designs that meet the principles of life extension (25–29); the use of renewable energy (11, 28); ease of disassembly (29); ease of product maintenance (11) and updating (25); and sharing products and services, for example through the use of the internet and information technology (1, 16) and even by adopting the product service system (PSS) (9).

Concern over extension of the product’s useful life cycle also makes it necessary to extend the use of products that compose the product portfolio (27), preventing them from becoming obsolete from a physical and emotional point of view (25). The physical obsolescence of products can be avoided through projects that allow remanufacturing, reuse, remodelling and recycling (6, 11, 28, 29). From the emotional point of view, products should involve the consumer over a long period of time (emotional durability) (25); this is a challenge, especially for designers and the area of marketing (27, 30).

In prior research, Stahel (31) proposed that businesses rooted in linear production systems need to look towards new service-oriented business models to close resource loops. In this context, the definition of servitisation has coalesced as the process of building revenue streams for manufacturers from services (32). From an industrial perspective, a transition from a linear to a closed-loop system requires a move from the conventional model of selling physical products to selling access to functionality or service. In such service-based business models, including leasing or pay-per-use, the manufacturers retain ownership of their products and take them back after use for the purpose of value recovery and redistribution (33).

This new circular product design perception is founded on the fact that a proportion of all the materials ever extracted are in today’s built environment (34). In circular product design, most products that would have been disposed of in the linear model are reused, for example as a raw material. Thus, the value of raw materials is kept within the system for the longest possible time (35). A circular design offers the opportunity to meet emerging consumer needs and respond to dynamic technological changes as well as social changes that require more sustainable solutions (13). The nature of the circular product design process is to understand early failures and uncertainties in order to continually iterate toward better environmental solutions (13).
3. Research Method

Aiming at reducing the gap in practices, barriers and drivers of CE integration into NPD, this research comprised case studies in three large- and medium-sized Brazilian companies that have environmental concerns and that are deeply involved in NPD activities. We intentionally considered ISO 14001-certified companies or companies that are currently implementing this certification since they tend to adopt more appropriate environmental management practices (36). The case study method was chosen because, besides being a useful approach to increase knowledge about certain topics, it allows an analysis of the researched situations, as the study is accomplished through interviews, observations and document analysis, allowing a better evaluation of the context (37).

Considering that it is an emerging topic and has been recently discussed (9, 12, 27), the qualitative procedure was the most appropriate. According to Yin (37) and Eisenhardt (38), the method is adequate when seeking a better understanding of the facts. To gain familiarisation with the object of study and to capture and understand the perceptions of the professionals involved with the integration of CE practices into NPD processes, the application of this qualitative method with the presence of a researcher in the field was considered important (37). The process of data collection was subsidised by a documentary analysis of companies’ policies and reports and involved observation and interviews with key respondents. The Appendix presents the case study protocol.

In addition to being located in Brazil, an emerging economy, the criteria for selecting the companies also included the following aspects: (a) to have implemented or be in the process of adopting ISO 14001 certification; (b) to develop and manage a broad portfolio of products that have environmental concerns; (c) to be involved in NPD activities; and (d) to provide full access to the researchers. In order to maintain the confidentiality of the participating companies, we designated them as Companies A, B and C. In Company A, the sustainability manager and the technology development manager joined the interview. In Company B, the regulatory matters manager and quality analysts were interviewed. Finally, in Company C, the environmental manager participated in the interview. Table I presents a characterisation of the companies studied.

4. Results

The presentation of the results was classified into three topics: circular practices; drivers and motivations; and barriers.

4.1 Practices for Integrating Circular Economy into New Product Development

Regarding practices for integrating the CE into NPD, Company A has been designing products considering the use of production waste, residues and used products to develop families of dishes and shower products. The adoption of reverse logistics programmes and partnerships with major retailers in Brazil has enabled the company to receive used materials. This was clarified by the following observations:

"We anticipate the use of waste from the own dishes produced in new products and this is already established in the product design. For example, we take the scraps and reuse them..."
within the new projects instead of carrying this waste to the landfill.”

Sustainability manager, Company A

“There is a reverse logistics program for electric shower. This product has a lower life cycle. Besides, it is composed mostly of plastic, which has high recyclability. We have partnerships with retailers to forward this shower already used and offer financial compensation in the purchase of a new one.”

Sustainability manager, Company A

Company C highlighted the use of environmental assessment throughout the entire life cycle of its products. Regarding circularity, the adoption of product design practices that use recyclable material as well as the extension of the life cycle, especially of the plastic incorporated into batteries, was observed. According to the environmental manager: “In the case of plastic, the life span is long and ends after the battery”. In addition, Company C pointed out a concern about investigations that indicate materials to replace the virgin raw materials currently used in its products. Partnerships between companies and universities were recommended to reduce this gap. In Company A, the PSS model was mentioned as a future trend. Respondents indicated that the firm already has floor rental projects for corporations and residences, which will have measured performance and other services added to those floors with the use of industry 4.0 technologies.

Company B does not adopt specific tools for NPD and environmental management, such as eco-design, but it has some internalised practices. The reuse and recycling strategies are considered only in the production process, but the company indicates strategic plans to implement policies of reuse and extension of the product life cycle that can make them the protagonist of this process.

4.2 Drivers for Adopting Circular Economy into New Product Development

The first driver found for the adoption of CE in NPD in Companies B and C is consumer demand for environmentally sustainable products. In addition, Company A also mentioned the environmental issues currently experienced by several Brazilian cities as motivation for the development of ecologically sustainable products. Company A justified that by illustrating the water crisis of 2014 faced by Brazil and, especially, the state of São Paulo. According to the interviewee, the situation stimulated the company to develop products that consume less water during the in-use phase of their life cycle: “With water scarcity, people are beginning to think more about water saving and us about eco-efficient products”.

Companies B and C highlighted the role of customers as a stimulus to improve environmental performance. In this sense, customers of Company C (mainly the automotive market) have demanded from their main suppliers the adoption of specific environmental practices and ISO 14001 certification, affecting product development activities. Company C also emphasised compliance with environmental legislation and standards as a means of stimulating and driving the company towards adopting circular practices in NPD. Brazil’s National Solid Waste Policy was widely cited throughout the interviews in the three companies as a standard that has guided environmentally sustainable practices in product development.

Furthermore, Company B highlighted a longer product life and lower fuel consumption during the use stage as a way to meet customer needs and thus make products more competitive. The interviewees pointed out that this concern, besides assisting customers’ demands, also generated positive environmental impacts:

“We have developed machines that consume less fuel and cause less impact on the soil, creating distinctive features. It leads to cost reduction, with higher productivity and less fuel use and also to lower weight and, consequently, reduced impact on the environment.”

Regulatory matters manager, Company B

4.3 Barriers to the Incorporation of Circular Economy into New Product Development

Among the main barriers observed for the incorporation of the CE into NPD were infrastructure characteristics of cities and awareness and education of the population regarding sustainability. Company B mentioned that an obstacle to the incorporation of the CE into NPD is the poor general education of society in the environmental
domain, which affects process activities and the development of new products. According to the company’s regulatory matters manager:

“There is a lack of environmental awareness of the people on the consumption and disposal of products, even with our everyday rubbish such as the plastic coffee cups used in the company.”

Regulatory matters manager, Company B

Companies A and C mentioned infrastructure-related barriers to incorporating the CE into NPD. Respondents at Company A pointed out that even while developing products that are eco-efficient in terms of water consumption, the basic sanitation and the drainpipe conditions of many cities do not allow such planned savings in product design, such as water for the flush toilet. According to the sustainability manager of this company: “Due to infrastructure condition and sewage systems, you cannot reduce the volume of water used in the flush toilets”. In addition, he emphasises: “The trend is to use less and less water for this type of product, but for that, you have to overcome the infrastructure barriers of the countries”.

Reinforcing the infrastructure aspect, Company C mentioned that, unlike automotive batteries, which already have a well-structured and cost-effective reverse logistics process, the company faces an obstacle in reverse logistics for the packaging of batteries with returnable material (mainly cardboard). In addition, the cost of reusing this material is not attractive from a financial perspective, discouraging the development of a product considering the reuse of raw material.

Another barrier pointed out by Company B concerns the competitive scenario in which it is inserted. Although its competitors engage in a discourse of sustainability, it was observed that the development of new products is oriented to the specific needs of the market that it reaches (business-to-business). That is, it aims to add more value to the customer, better product performance and lower costs, instead of implementing innovations that promote sustainability and may affect profit margins or price.

5. Discussion and Final Remarks

The topic of the CE and especially the integration of its principles into the NPD process is coming to light. Despite their recent importance, it is challenging for manufacturing firms to embrace these principles. Some studies have already proposed ways to incorporate these principles into NPD (2, 11), but very few provide support for these issues in real situations in companies. This article contributes to theory and practice by identifying how companies concerned with environmental sustainability have adopted some of these practices.

When we compared our findings with the literature, we noticed that the companies studied are still in the early stages of adopting and making CE viable starting from the product design stage. For instance, contrasting the practices of these companies with the ReSOLVE framework (5) indicates that the firms have a long way to go before fully incorporating CE into NPD. The level of maturity in management should also be considered when analysing and proposing the incorporation of the principles of the CE. Company A, for example, seems to be more structured and mature than the others; it has already adopted a higher set of circularity-oriented practices from the early stages of the NPD process. It is also interesting to observe that none of the companies cited projects that avoid the physical obsolescence of their products. Table II shows the barriers and opportunities contributed by this article to the literature for the adoption of CE into NPD, in addition to the highlighted practices. Regarding practices for the integration of CE into NPD, the project started by Company A to adopt the PSS model for ceramic flooring by integrating emerging technologies stands out. National legislation oriented to CE, such as the National Solid Waste Policy in Brazil, also contributes to the adoption of circular practices. It is known that there is specific legislation for the CE in several regions in the world, such as in the European Union and China.

As indicated by Company A, national and municipal infrastructure issues, such as inefficient systems, are obstacles to adopting CE practices in NPD. In this case, it is observed that the macro level of the CE (for instance, government actions) impacts the micro level, that is, it hinders the adoption of practices towards circularity in companies. This finding brings implications especially for emerging nations, which on the one side are seeking to advance and promote environmental practices following developed countries, but on the other, still have difficulties in providing infrastructure for the population.

In line with other studies (20, 41), it was also observed in Companies B and C that the use of circular products may be more expensive and less attractive to consumers, which represents...
a significant challenge (24). It seems to be an interesting finding since, on the one hand, there is consumer demand for eco-friendly products and on the other hand, there must be a balance regarding the price to be paid for those environmentally sustainable products.

Accordingly, Company B emphasised that a barrier to CE stems from a possible increase in the cost of its products caused by the adoption of circular practices. In this way, breaking market barriers can lead to customer losses due to higher prices and margin losses, ultimately affecting financial results and shareholders. Therefore, resolving the dilemma between customer requirements, competitors’ offerings and the challenges of circularity is relevant to future studies on CE.

Among the managerial implications, we highlight the possibility of integrating circular product design practices, such as those presented and discussed in this study, into specific business models and oriented to circular business models, such as that proposed by Hofmann (42), which contemplates not only product development activities but also aspects such as the application of new technologies (such as digital) and stimuli for consumer behaviour changes to assist managers in the transition from linear to CE.

In addition to the practices associated with circular product development (such as product sharing; design for updating; Reduce, Reuse, Recycle (3Rs); ease of disassembly and product maintenance, among others), and in light of the drivers and barriers identified and discussed in this study, it is important that managers interested in the development of circular products monitor the willingness of market segments to purchase products or components derived from reuse, recycling and sharing, among others. In the same way, when the circular product is more expensive than the traditional or linear product, it is also relevant to study the willingness of customers to purchase these products. Thus, boosting demand for circular products may be a strategy for companies and governments interested in stepping up CE adoption.

A noteworthy result is that legislation can be both a driver and a barrier to CE adoption. This was observed in the theoretical review and also in the case studies. As a stimulus, if legislation is in line with CE principles, it can drive companies to develop circular products. By adopting these practices from product design activities, the environmental impacts of the product throughout its life cycle tend to be significantly lower. On the other hand, vague legislation or even the absence of legislation tend to discourage companies from adopting CE (21, 43), representing a barrier to its implementation.

This result also has implications for policymakers. These implications arise from legislation as a major element in stimulating (or discouraging) firms’ CE adoption and customer behaviour. Given this, national or regional governments need to draft legislation that effectively encourages the adoption of CE principles while at the same time lowering possible barriers. It is essential for laws to be designed that push companies to opt for product designs that are easily updated, disassembled, remanufactured, reused and consider the use of biodegradable materials, for example.

Additionally, policymakers could raise and discuss with companies interested in adopting CE, the urban and infrastructure problems that lead to

<table>
<thead>
<tr>
<th>Dimensions</th>
<th>Synthesis of results</th>
<th>Literature</th>
<th>References</th>
</tr>
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<tbody>
<tr>
<td>CE practices</td>
<td>Use of recyclable material and reuse of waste; extension and assessment of product life cycle; incorporation of services and new technologies (such as PSS); adoption of reverse logistics programmes</td>
<td>Regenerate Share Optimise Loop Virtualise Exchange</td>
<td>(2, 5, 16, 39, 40)</td>
</tr>
<tr>
<td>Drivers when adopting CE into NPD</td>
<td>Consumer pressure; country legislation (for example, in Brazil, the National Solid Waste Policy)</td>
<td>Institutional, governmental and legislation; economic factors; consumer preferences</td>
<td>(2, 7, 20, 21, 40)</td>
</tr>
<tr>
<td>Barriers when adopting CE into NPD</td>
<td>National and regional environmental problems; problems of urban infrastructure (water pipes, for example); increase in the cost of products</td>
<td>Economic and financial uncertainty; organisational and managerial issues; technological advancements</td>
<td>(2, 20–24, 41)</td>
</tr>
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wastage of resources such as water and energy. Benchmarking with successful existing legislation can also help guide governments in encouraging CE adoption. In this line, we suggest that future studies identify and analyse these cases of benchmarking. Finally, this study has some limitations that should be recognised. The main one is related to the research method adopted. Although we applied a multiple case study, the results presented cannot be widely generalised since it was based on only three companies and a single-country perspective – an emerging context. Therefore, it is recommended that future studies identify, analyse and disseminate other practices, barriers and stimuli for the adoption of CE into NPD in a larger number of companies and in those that operate in different countries and economic contexts.

Acknowledgments

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Appendix

Case Study Protocol

Research question: How have companies integrated CE into NPD? What are the practices, barriers and drivers to the development of circular products?

Unit of analysis: Integration of CE into NPD; practices; barriers; drivers.

Organisations: Three Brazilian companies that implement or are implementing ISO 14001 certification.

Sources of data and reliability: Cross-referencing of data collected through interviews with target respondents, documentary analysis and observation.

Construct and external validity: Multiple sources of evidence (interviews, observation and documents). Replication logic in multiple case studies and discussion of empirical results in light of the state-of-the-art.

Examples of key questions of the questionnaire:

- Does the company have projects in which product development has a direct alignment with environmental sustainability? Does the company implement cradle-to-cradle approach practices? Is there any product or project that uses recycled or reconditioned materials as raw material? Are there reuse policies in new product designs? How does it occur? What are the end-of-life concerns about products? How does reverse logistics or the proper disposal policy work? Are these aspects incorporated into new product planning? What are the main challenges the company faces in implementing circular product development practices? What are the drivers or reasons for the company to integrate CE into product development?

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As citizens, organisations and governments across the globe increase their interest in environmentally and socially sustainable means of production and consumption, the idea of a circular economy (CE) has been at the forefront of recent discussions held at organisational, national and international levels. This article briefly presents the CE concept from a supply chain management perspective. Then, two contemporary, representative CE technology management problems are introduced. The article concludes with some takeaways that policy makers and managers can use to inform further CE development.

1. Introduction

The United Nations (UN) World Commission on Environment and Development defines sustainable development as a trajectory where future generations are secured the same level of welfare as present living generations (1). The economic implication of this approach is a requirement for constant and regenerative utility (2). The global middle class is estimated to double in size to nearly five billion by the year 2030 (3). As the number of middle-class consumers increases, natural resources required to support population expansion are rapidly decreasing (4). In addition, the waste generated by first world economies is estimated to be 3.5 million tonnes per day; the amount of waste generated will grow proportionately with the number of middle-class consumers throughout the world (5), approximately 2 billion tonnes of solid waste are produced each year by the world’s cities, roughly half of which is organic waste (6). Thus, strategies that support sustainable industrial initiatives to emphasise the reclamation and retransformation of resources need to become more ubiquitous in order to support global population growth and subsequent increases in consumption.

The European Union (EU) recently set a strategy to transition towards a CE by adopting a ‘closing the loop’ approach to industrial production systems. One of the goals of this strategy is to maintain the value of products, materials and resources in the economy for the longest time possible, in consideration of waste minimisation (7). CE is a regenerative approach to sustaining consumption requirements while preserving natural resources (8) and can be defined as “a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling” (9). For any given organisation, adopting a CE approach entails incorporating strategies, policies and processes that consider environmental performance, waste reduction and efficient consumption across the entire supply chain network (10).

The proper leveraging of technology is already proving to be a necessary condition for developing...
and sustaining both large and small CE initiatives alike. However, not only is the idea of CE new and somewhat daunting, but the emerging technologies upon which these CE networks will be operated are not well understood even by those who manage today’s linear supply chains. This article introduces CE from a supply chain management perspective and introduces two supporting technologies for the purpose of informing current and future stakeholders about CE technology management.

2. Circular Economy as a Closed-Loop Supply Chain

As the interest surrounding CE continues to grow, supporting supply chain practices are also gaining more attention. From a supply chain perspective, CE is based on many of the same concepts used to employ business-to-business closed-loop systems. These systems are typically in place to support the lifecycle of large or expensive assets such as aircraft and large machinery. Conversely, business-to-consumer models historically employ more linear concepts, where products are delivered to consumers, who then chose if, and if so, how to maintain and dispose of them. In essence, CE is the operationalisation of a business-to-consumer closed-loop supply chain system. As such, there is a lot that can be learned from business-to-business closed-loop supply chain best practices. Such practices include increasing resource reuse throughout the supply chain, increasing resource efficiency, dematerialising waste through resource conversion and slowing the amount of new resources introduced into the system via product life cycle extension (11).

Managers and policy makers are promoting CE as a means of sustainable resource consumption (12). However, the transition from a linear economy to a circular one requires fundamental changes in the way businesses are currently operated (13). While change in itself is often a difficult process to manage, making these changes might be worth the effort in that it can leverage opportunities to introduce new, more sustainable business models.

For example, HP Inc, USA, closed-loop printer ink programmes have reduced waste associated with consumer printing by 67% (14). In addition, Italian fashion brand company Calzedonia Group promotes a recycling campaign that incentivises in-store drop-off of all types of used garments via store credit. These garments are then recycled and, to date, the company has collected over 2 million kg of clothing that has been subsequently recycled (15).

In another example, Nestlé, Switzerland, estimates that it produced about 1.5 million tonnes of plastic in 2018. Recognising the negative ramifications of this production, the company announced that it strives to make 100% of its packaging reusable or recyclable by 2025 and has recently begun an initiative to eliminate all plastic straws in its products (16). Those are some of many examples where CE can be implemented to produce a win-win for all stakeholders (i.e. consumers via lower prices; environment via lower resource usage; producer via lower production costs).

Perhaps other organisations can adopt similar programmes that have the opportunity to improve both environmental and economic performance. In today’s technology driven supply chains, the importance of leveraging existing and emerging technologies that help to enable CE cannot be understated. In the next section, two supporting technologies are described as a means to demonstrate the role of technology in making CE a reality.

3. Circular Economy Technologies

Many of today’s CE challenges are driving technological advancements as a means to close the loop and reuse resources. Although there are indeed many challenges to implementation such as motivating new consumption behaviours, redesigning supply chains and revamping regulation, governments and managers alike continue to build and leverage technology to support their CE initiatives. In fact, Korhonen et al. (17) suggest that, when CE processes are effectively combined with appropriate technological innovations, the result has significant positive impacts on several echelons and levels of contemporary value chains. This pairing is proposed to lead to transformation in favour of both the environment and economic growth (18).

As such, CE participants require a robust strategy to plan and manage increasing complexity across their supply chain processes that support CE (19). New technologies will play a prevalent role in CE development (20) and help to shape fundamental strategies for organisations seeking to participate in CE (21). These technological advancements will not only help improve industrial processes and operations, but also help to integrate the critical role of the consumer (22). Two major categories of technological innovation deal with the multidisciplinary problem of plastic manufacturing and recycling and the employment of big data
analytics (BDA). The following subsections describe these technologies.

**3.1 Plastics**

Less than 15% of plastic waste is collected for recycling while the rest is put in landfills, incinerated, moved to less-developed nations or abandoned completely (23). Approximately half of all plastic ever produced has been manufactured since 2000 (24). Unfortunately, recapturing plastic waste has been problematic for many reasons. For instance, polypropylene (resin identification code 5) cups and lids promoted as recyclable by fast food restaurants are not recyclable in a growing number of places of the United States (25).

Current chemical recycling technologies can return used plastics into their original naphtha (petroleum) form, at which time they can be converted into new polymers (26). However, these processes are seen by many as cost restrictive in that new plastics are cheap and already clean and the cost to recycle is often more than the cost to discard and simply make new plastics. As such, recycling of plastics and many other raw materials is declining in favour of more cost-effective practices, despite the negative environmental impacts.

The EU is a first mover among large governmental institutions to support CE initiatives and has recently put into place strong policies with goals such as making all plastic packaging recyclable, compostable or reusable by 2030 (27). Consequently, governments and other institutions seek innovations related to the plastics industry. As one example, a report by the World Economic Forum reveals that bioplastics represent one of the most important breakthrough technologies expected to radically impact the global social and economic order (23). Similar CE technologies facilitate making plastics from urban food waste (28, 29) or lignin from plant waste (30), which increases material strength without using crops that could otherwise be used for food. From a CE perspective, these wastes can be seen as a resource, not simply a cost to manage.

**3.2 Big Data Analytics**

BDA is seen as an imperative for designing and implementing CE strategies (31, 32). Insights derived from BDA facilitate decision-making in sustainable production (33). In CE, these insights can be leveraged to integrate processes (both internal and external) and facilitate resource sharing. As shown in Figure 1, managers start with identifying shared goals with internal and external partners. Then, the employment of technologies that enable better information sharing and relationships among members of the network add value that goes beyond the transactional level and thus creates true knowledge-sharing networks. This synergistic approach facilitates the ability to sense and seize problems and opportunities across the CE ecosystem. In the end, collaboration, visibility and transparency across processes and between organisations allows supply chains to achieve several goals, such as: to improve customer service and fulfilment, to react faster to supply chain disruptions, to increase efficiency, to improve integration and to better monitor product life cycles (34).

Disruptive technologies (such as cloud computing, the internet of things, machine learning and artificial intelligence (AI)) might eventually become a part of the CE ecosystem and will need to be constantly monitored and assessed for their usefulness to develop new CE business models and address current challenges presented by CE operations. Good supply chain partners should jointly monitor information, people, processes and decisions made regarding a product throughout its entire life cycle (35) using these advanced, complimentary technologies.

Managers appreciate the operational complexity surrounding the large-scale implementation of consumer-focused closed-loop supply chains. This can lead to resistance to adoption of CE practices. However, this resistance can be allayed when existing or new BDA processes are used to generate greater understanding of operational-level elements and how they relate to higher-level CE strategy.

**3.3 Other Technologies**

Supply chain digitalisation efforts are driving the way organisations compete with their supply chains. These technologies include additive manufacturing, AI, augmented reality, blockchain, cloud computing, internet of things and many others (36). Although it is beyond the scope of this article to go into detail, we briefly describe some of these technologies and uses next.

One of the most prominent technologies today is AI. As a facet of AI, machine learning suggests “the machine’s ability to keep improving its performance without humans having to explain exactly how to accomplish all the tasks it’s given” (37).
The near future will see humans working further to structure extant complex problems such that appropriate inquiries can be formulated to leverage the computational advantages presented by ever increasing machine capabilities. It is thus imperative to understand how to strike the right balance between human and machine interaction (38). To face increasing environmental challenges, companies and researchers are developing AI assisted robotic technologies that can work with humans to optimise processing of recycled materials in terms of sustainability, efficiency, profitability and safety (39).

The advent of blockchain technology has brought the discussion of trustless systems to the forefront of both academic and business discussions. Blockchain denotes a secure database system based on distributed ledger technology, where business rules dictate automated consensus algorithms that serve to validate and write transactions to an immutable ledger that is distributed across a given network of computers. Companies are currently using blockchain for track and trace and financial transaction applications and are realising benefits related to transparency, trading partner trust, provenance validation and transaction costs. These benefits can help to enable accountability and consistency in CE networks.

4. The Road Ahead

Here is a summary of key takeaways for managers and policy makers who are new to CE or charged with implementing its concepts:

- Transition to CE will be successful only if all parties involved in the supply chain (including the consumer) are involved and committed. This works if the new business model will create value for all stakeholders via advancing more sustainable closed-loop systems.
- Supply chain collaboration is essential when it comes to transforming a business to CE.
- The future of CE as a viable and profitable business model depends on technologies that

![Fig. 1. A stakeholder view of using BDA for CE. Reprinted from (32) with permission from Elsevier, copyright (2019)](image-url)
will enable organisations to move beyond participating in the current linear (cradle to grave) paradigm and advance to the circular (cradle to cradle)

- BDA and related technologies will be key drivers to help economies become more circular. Advancements toward this end will require multidisciplinary expertise in order to inform new processes and organisational constructs. Logistics and supply chain management skills are fundamental for the successful reorganisation of processes and policies aimed at closing the loops
- BDA and associated AI-related technologies can be employed to help organisations measure and control their impacts
- Solving the zero-trust problem is critical for supply chain management and global trade. Technologies like blockchain might be leveraged to solve this problem
- The role of consumers is a significant determinant of CE success. Consumers are no longer the final position in the supply chain, but serve as an important, decision-making actor within the supply chain
- Organisations that organise and manage their CE processes in order to allay societal and environmental consequences will be better positioned to compete on economic, environmental and social performance
- A critical component of advancing CE initiatives includes managing closed-loop supply chains at the business-to-consumer level. Several CE objectives can be achieved only when an efficient and effective closed-loop system is well designed and managed.

5. Conclusion

This article introduced CE and discussed two areas of technological innovation that are helping to initiate and support CE initiatives: plastics innovation and big data analytics. Of course, there are several other technologies that are being used to close the supply chain loop and make CE a reality, as also discussed. However, we submit that the technologies discussed herein are representative of extant CE technology management problems in that they both require and facilitate multidisciplinary collaboration, information sharing and the inclusion of relevant stakeholders (especially consumers who are becoming important nodes in the supply chain, rather than the end point of a linear production process).

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Review and Outlook of China Non-Road Diesel Mobile Machinery Emission Standards

Stricter emissions standards for better air quality in China

1. Introduction

Non-road diesel mobile machinery includes construction machinery, agricultural machinery, tractors, generating units, inland waterway vessels and ground service equipment in airports, among which construction machinery and agricultural machinery are dominant. By 2017, the amount of construction machinery in China had increased to 7.2 million units and the total power of agricultural machinery had increased to 767.763 million kW. As shown in Figure 1, the total emissions of nitrogen oxides (NOx) and particulate matter (PM) from construction machinery and agricultural machinery were 3.652 million tons and 320,000 tons respectively (1), which is comparable to the amount of the pollutant emissions from diesel vehicles in the same period. Non-road diesel mobile machinery has become the main source of emissions in China.

Similar to the USA and the European Union (EU), air pollution control for non-road engines starts with non-road diesel mobile machinery in China. Based on analysis of the current standards in China and the latest progress in relevant international emission standards and regulations, this paper outlines vital issues for developing new non-road mobile machinery emission standards in future and provides some recommendations for formulating non-road mobile machinery emission standards.

2. Development of Emission Standards for Non-Road Diesel Mobile Machinery

In 2007, China issued 'Limits and measurement methods for exhaust pollutants from diesel...
engines of non-road mobile machinery (I, II)’ (GB 20891-2007), which is applicable to diesel engines whose rated net power is less than 560 kW. The requirements of China stage I/II emissions standards were similar to those of the EU stage I/II. However, considering that a large number of non-road diesel engines under 37 kW are produced and used in China, the emission requirement on diesel engines under 37 kW has been put forward since China I. China I emission standards were implemented on 1st October 2008 (refer to production, import and sale dates below) and China II standards were implemented on 1st October 2010.

In 2014, China issued ‘Limits and measurement methods for exhaust pollutants from diesel engines of non-road mobile machinery (III/IV)’ (GB 20891-2014) and the application scope of this standard was further extended to diesel engines with rated net power over 560 kW. The limits of these two stages were based on EU stage IIIA/IIIB and its application scope is wider, ranging from under 19 kW to over 560 kW. China III became effective from 1st October 2015 and all non-road mobile machinery manufactured, imported and sold must meet the requirements from 1st April 2016. The NOx (or NOx + HC) and PM limits from China I to China IV are shown in Figure 2 (2, 3).

The focus of emission control for non-road mobile machinery diesel engines are NOx and PM and based on the maturity and the difficulty of control technology, as well as the increase in cost, the emission limit for diesel engines of 37–560 kW was tightened the most. Compared with China I, the NOx limit is tightened by 50–80% and the PM limit is tightened by 95–97% in China IV. For diesel engines below 37 kW, the NOx and PM limits have been tightened by 30–40% and for diesel engines over 560 kW, which have been controlled since China III, the emission limits have been tightened by about 40%.

In cycle tests, only the non-road steady-state cycle (NRSC) was used in China I to China III, including the C1 cycle for most variable speed engines, D2

Fig. 1. Contributions of light-duty, heavy-duty vehicles and non-road diesel mobile machinery to: (a) NOx emissions; (b) PM emissions (1)

Fig. 2. Development of (a) NOx and (b) PM limits of non-road diesel engines in China (2, 3)
cycle for constant speed engines and the G2 cycles for variable speed engines with rated power below 19 kW. These cycles are specified in ISO 8178 and each cycle contains a series of operating modes that specify the speed and torque, with different weighting factors to calculate the pollutant emissions of the whole cycle (see Table 1).

There are different varieties of non-road mobile machinery and the actual operating conditions of different machines vary greatly, so NRSC has certain limitations in assessing the actual emissions of the machinery. Therefore, in China IV, the non-road transient cycle (NRTC, see Figure 3) is introduced to test variable speed diesel engines (excluding marine diesel engines) with a power range of 19–560 kW and variable-speed multi-cylinder diesel engines below 19 kW (4).

NRTC is an engine dynamometer transient driving schedule of total duration 1238 s and a composite test cycle consisting of a representative duty cycle for seven common types of non-road equipment with improved accuracy. The NRTC is

<table>
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<th>Table I NRSC Test Cycle</th>
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<tbody>
<tr>
<td>Mode number</td>
</tr>
<tr>
<td>Torque per cent, %</td>
</tr>
<tr>
<td>Speed</td>
</tr>
<tr>
<td>Weighting factors</td>
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[Fig. 3. NRTC normalised dynamometer schedule (4)]

Fig. 3. NRTC normalised dynamometer schedule (4)
run twice after completion of pre-conditioning, the cold-start run and the hot-start run. Composite weighted emissions are computed by weighting the cold-start run results by 10% and the hot-start run results by 90% (5).

3. Recommendations on China’s Future Non-Road Mobile Machinery Regulation

The limits and NRTC test cycle of China IV were proposed in GB 20891-2014, and the specific technical requirements will be supplemented later. Based on China’s air quality improvement needs, as well as the development and progress of emission control technology and testing technology, this paper proposes the following suggestions for future emission standards of non-road mobile machinery.

3.1 Emissions can be Further Reduced by Using Advanced Emission Control Technologies

China aims to strike a balance between humans and nature to make notable achievements in reducing emissions by 2020, as well as to garner fundamental improvements in its ecology by 2035. The State Council has released the ‘Three-Year Action Plan to Win the Blue Sky Defence War’, in a bid to improve air quality. By 2020, emissions of sulfur dioxide (SO\(_2\)) and NOx should decline at least 15% from 2015 levels, while cities with low air quality standards should see their PM 2.5 density fall at least 18%, according to the plan (6). Diesel vehicles and non-road diesel mobile machinery are the main sources of air pollution in China, especially in cities. The action plan for diesel truck emissions control was released at the end of 2018 and includes emission control for diesel vehicles and non-road diesel engines. All these policies require stricter and more effective non-road mobile machinery emission standards to be developed and implemented in the future in China.

China III emission standards have been implemented for four years. At the present control level, engines can meet the standards without any exhaust after-treatment system. In 2018, the Ministry of Ecology and Environment of China issued the ‘Technical Policy for Pollution Prevention and Control of Non-road Mobile Machinery’, encouraging China IV and China V to adopt advanced emission control technologies, such as selective catalytic reduction (SCR) and diesel particulate filter (DPF) (7). It can be seen that by adopting advanced emission control technology, NOx and PM from non-road mobile machinery can be significantly reduced. The NOx and PM limits will be tighter in future regulations, and the particle number (PN) emission requirement also will be proposed.

3.2 Real World Emission Reduction Should be Focused on

Increasing studies suggest that the traditional laboratory test methods centring on a specific working cycle cannot truly reflect the level of vehicle emissions (8–10) and results may greatly differ from those obtained in actual use (11). Reducing emissions in actual use has become a major direction for the development of emission regulations in various countries and regions. The United States Environmental Protection Agency (US EPA), the EU and China have successively added measurement requirements for real road emissions to the regulations for heavy-duty and light-duty vehicles (12, 13). The same problem exists in non-road mobile machinery, so EU Stage V has added this measurement requirement when the machinery is working, but has not yet set a limit (14).

At present, emissions testing of non-road diesel mobile machinery in China is completed using the engine test bench. In our study, 16 non-road mobile machines (see Table II, all the engines meet

<table>
<thead>
<tr>
<th>Machinery number</th>
<th>Machinery type</th>
<th>Engine power kW</th>
<th>rpm</th>
<th>Model year</th>
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<tr>
<td>1</td>
<td>Rubber tyre loader</td>
<td>162</td>
<td>2000</td>
<td>2017</td>
</tr>
<tr>
<td>2</td>
<td></td>
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<td></td>
<td>273</td>
<td>1350</td>
<td>2015</td>
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<tr>
<td>8</td>
<td>Backhoe loader</td>
<td>120</td>
<td>2000</td>
<td>2016</td>
</tr>
<tr>
<td>9</td>
<td></td>
<td>124</td>
<td>2000</td>
<td>2016</td>
</tr>
<tr>
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<td>Forklift</td>
<td>85</td>
<td>2200</td>
<td>2018</td>
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<td>2017</td>
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<td>12</td>
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<td>110</td>
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<td></td>
<td>150</td>
<td>2100</td>
<td>2017</td>
</tr>
<tr>
<td>15</td>
<td>Corn harvester</td>
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</tr>
<tr>
<td>16</td>
<td></td>
<td>135</td>
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<td>2016</td>
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</table>
China III) from different OEM were tested based on the method of portable emission measurement system (PEMS). The results show that the emission of NOx is 1.5–2.25 times greater than that of the engine limit (see Figure 4).

The actual working conditions of machinery change frequently and the working environments vary. The engine test bench’s environment conditions are relatively stable and the test conditions have been quantified, so the manufacturer can adjust the emissions characteristics of the diesel engine under the test conditions, resulting in excessive emissions in actual operation. Therefore, in order to reduce emissions during the actual operation of mobile machinery, Chinese non-road diesel mobile machinery emission standards should focus on the following issues in future: proposing a method of measuring the whole machine and reasonably setting limits according to the actual operation conditions and the working environment.

### 3.3 Focus on Monitoring the Actual Emissions

In order to meet the increasingly stringent emission control requirements, non-road mobile machinery has also begun to use exhaust aftertreatment systems to reduce emissions of pollutants such as NOx and PM. If the emission control device fails or performs poorly, the corresponding pollutants may multiply. In this study, two mobile machines using SCR were tested using PEMS. When urea solution is replaced by water, the emission of NOx increases nearly 20 times (see Figure 5). It can be concluded that whether the exhaust aftertreatment system works normally or not will directly influence the emission level of the machinery.

In order to monitor whether the key components work normally or not and to ensure the mechanical emissions meet the requirements of the regulations for the whole lifetime of the
vehicle, many countries and regions have put forward requirements for an onboard diagnostic (OBD) system and NOx control system on the vehicle. This concept has been applied to non-road mobile machinery. In EU Stage V, the functional requirements of a NOx control diagnostic (NCD) system and particulate control diagnostic (PCD) system for NOx and PM control systems respectively are put forward. In case of failure, the warning and inducement torque reduction systems will be activated, as shown in Figure 6 (15). Therefore, Chinese non-road diesel engine emissions regulation should include the requirements of onboard emission control and diagnostics systems in the future.

In addition, China has put forward the requirement for remote emissions monitoring in the stage VI national standard for heavy-duty vehicles (‘Limits and measurement methods for emissions from diesel fuelled heavy-duty vehicles’ (GB 17691-2018)), stipulating that the OBD system has the function of sending monitoring information in real time to better monitor the emissions of vehicles running on roads, to judge the actual emission of vehicles and determine whether the various emission control measurements and OBD work effectively and whether emission-related faults are repaired in time. This also suggests a new method of supervision for the emissions of non-road mobile machinery. At present, there is usually no registration system for non-road mobile machinery and no periodic inspection system for in-use machinery, so it is difficult for in-use machinery to achieve emission standards. The remote emissions monitoring technology from heavy-duty vehicles could be used as a reference and applied to non-road mobile machinery, providing a simple and feasible method for in-use machinery emissions monitoring.

3.4 Improvement of Fuel Quality

With the improvement of emissions standards, different aftertreatment systems need to be combined to reduce the final emission of pollutants. The application of aftertreatment system requires higher quality of fuel, especially the sulfur content. The sulfur content of reference fuel is 10 parts per million (ppm) in non-road stage IV regulation. Since 2010, reduction of sulfur content of fuel in China has been greatly accelerated. In 2013, the sulfur content in general diesel fuel decreased from 2000 ppm to 350 ppm; in 2017, the sulfur content was reduced to 50 ppm and in 2018, the whole country began to supply diesel fuel with 10 ppm sulfur content. The improvement of fuel quality is the basic condition to ensure the effective operation of emission control devices, which provides a guarantee for the implementation of more stringent emission standards for non-road mobile machinery in the future.

After the upgrade of fuel standards, it is important to strengthen the supervision of market fuel quality and ensure the supply and use of certified fuel. According to data released by the Ministry of Ecology and Environment in 2018, the per cent pass of diesel fuel in private gas stations of Beijing, Tianjin and Hebei and surrounding areas reached 50%. In response to the issue of fuel quality, the ‘Three-Year Action Plan to Win the Blue Sky Defence War’ released by the State Council was deployed to achieve the integration of vehicle diesel fuels and general diesel fuels and to crack down on the production, sale, storage and
use of unqualified fuel and urea, including banning unqualified gas stations (16).

4. Conclusions

In order to improve the air quality in China, stricter and more effective non-road mobile machinery emissions regulations should be developed and implemented in the future. The adoption of advanced emission control technologies will significantly reduce NOx and PM emissions. Emissions standards are the basic means of environmental management, so the formulation, content and form of emissions standards must serve environmental management needs. The main direction for future standards development is to reduce non-road mobile machinery pollutant emissions in the real world. It is also necessary to establish an applicable and operational on-board measurement method and to develop an effective online monitoring system and method. Supervision on the quality of marketed fuel should be strengthened to ensure the effective implementation of emissions standards and achieve the expected effect of pollutant emissions reduction.

Acknowledgments

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The Discoverers of the Isotopes of the Platinum Group of Elements: Update 2020

New isotopes found for Pt

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Since the 2018 review (1) one new light isotope of mass 165 (2) and four new heavy isotopes of masses 209 to 212 (3) have been identified for platinum (Table I). The heavy isotopes are only identified as being ‘particle stable’ – that is resistant to proton or neutron decay but all are expected to decay by beta decay in which an electron and anti-electron neutrino are emitted when a neutron in the nucleus decays to a proton, so that the mass number of the daughter isotope remains the same but the atomic number is increased by one. The light isotope decays by alpha decay in which the emittance of a helium four ion means that the daughter isotope mass is four lower than the original parent isotope whilst the atomic number is reduced by two. The half-life is 0.4 ± 0.2 ms normalised from the reported value of 0.26 (−0.09 +0.26) ms.

<table>
<thead>
<tr>
<th>Element</th>
<th>Number of known isotopes</th>
<th>Mass number range</th>
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<tr>
<td>Ru</td>
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<td>85–125</td>
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<tr>
<td>Rh</td>
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</tr>
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<tr>
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<tr>
<td>Ir</td>
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<td>164–205</td>
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<tr>
<td>Pt</td>
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<td>165–212</td>
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Table II Total Number of Isotopes and Mass Ranges for Each Platinum Group Element to 2020

<table>
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<tr>
<th>Element</th>
<th>Number of known isotopes</th>
<th>Mass number range</th>
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<tr>
<td>Ru</td>
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<tr>
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</tbody>
</table>

References


The Author

John W. Arblaster is interested in the history of science and the evaluation of the thermodynamic and crystallographic properties of the elements. Now retired, he previously worked as a metallurgical chemist in a number of commercial laboratories and was involved in the analysis of a wide range of ferrous and non-ferrous alloys.
Introduction

“Raw Materials for Future Energy Supply” was published by Springer in 2016 and translated from German in 2019. It is part of the published series ‘Energy systems of the Future’ by a collaboration of German scientific academies: acatech-National Academy of Science and Engineering, Munich, Germany; Leopoldina National Academy of Sciences, Halle (Salle), Germany and the Union of the German Academies of Sciences and Humanities, Mainz, Germany. The book delves into the future supply of raw materials as a consequence of society, addressing primary and secondary resources and resource substitution. Discussions involve not only the technical details but also socioeconomic and ethical points of view. The energy sector is still a long way from being climate neutral, with many countries (especially Germany which is the focus of this book) pushing ahead with the development of new energy technologies. Emerging technologies create an increased demand for raw materials which in turn puts pressure on natural resources. This book targets anyone interested in the future raw material supply and how this interlinks with the development of renewable energies.

Fundamentals

Chapter 1 defines the changes that need to be made to minimise the environmental pollution and pollutants that originate from human activity. The authors determined that the emissions of carbon dioxide need to be reduced as quickly as possible, by moving away from the traditional methods of combustion of crude oil, natural gas and coal. As new technologies emerge for generating and storing energy, the demand for raw materials will also alter (increasing the use of metals, while decreasing our reliance on fossil fuels).

The fundamentals of natural resources are defined in Chapter 2 with the different classifications of natural resources available. It describes the differences between renewable and non-renewable materials, providing insights into materials that are not necessarily renewable but can still be recycled, such as metals. Many of the technology metals have only been used industrially during the last few decades. This is shown in Figure 1 where the number of chemical elements used by a steam engine, compared to modern solar technologies is significantly different.
The exploitation of minerals is categorised into reserves (mineral deposits that could be exploited economically with current available technology), resources (known deposits that cannot currently be exploited economically) and geopotential (occurrences and deposits that have not yet been identified). The link between these categories and consumption is discussed, looking at critical raw materials and those of strategic economic importance. Currently it has been determined that there is a sufficient supply of raw materials to meet the current demands, but market conditions can result either in short term shortages or increases in the price of the metal or mineral. When there is a shortage of a raw material, both the supply and demand side generally react. On the supply side more efficient recycling routes are often determined, while on the demand side there is a more economical use of the relevant natural resource.

Key to understanding which raw materials could be utilised in future energy systems is understanding the availability of these materials and extrapolating the information over the years to come. Political situations can also affect the supply of a material affecting whether it is classed as critical. Examples of this have been shown in Chapter 2, comparing reports compiled by different countries on the supply risk of manganese. The European Union (EU) classes the supply risk as low, due to the mine being controlled by a French company, whilst the USA classes the supply of Mn as high risk.

The information in these two chapters provides a good insight into the classification of raw materials, the terminology used when discussing the raw material market and understanding of the supply chain. It gives a flavour for how shifts in availability, cost and political situations can affect the supply chain. Though much of the information could be classed as common sense when thinking about topics individually, the detail compiled in this chapter helps tie it all together into one large picture.

**Supply of Raw Materials and Effects of the Global Economy**

The availability of raw materials is influenced not only by supply but also demand. Both are dependent on developments in mining and processing industries, global economy, environmental impact and political situations. Chapter 3 is the longest section in this book, delving into the analysis of the supply of raw materials. This chapter covers a range of topics from exploration and exploitation, price setting and understanding the demand for the materials, but for me some of the key points were:

- The social and environmental impact on the availability of raw materials
- Utilisation of renewable energies during the mining and processing of ores
- The available supply of secondary resources
- Technological advances, improving the supply of both primary and secondary resources.

For consumers, the application of raw materials is no longer well defined as the use of components in products is often complex. For example, the general public will recognise industrial products such as...
televisions, smartphones or electric vehicles, but will not always understand the raw materials that have been used during production.

One of the sub-chapters discusses how mineral exploitation in countries that are industrially advanced is a seemingly normal service industry that does not relate to technological progress. Whereas the indigenous populations of countries where the mining occurs can suffer serious consequences such as forced acquisition of their land and resettling. There can also be an impact on the landscape depending on whether the mine is based underground or a surface opening pit. The underground mine generally requires relatively small areas on the surface operating with minimal impact on the local environment. An open pit can cause vast changes to the landscape, villages may need relocating and the required surface areas may not be available for other uses for decades. To minimise both the social and environmental impact high standards need to be implemented, with industry taking responsibility for where the raw materials are sourced. Accountability should continue down the chain to the end user (customer). This chapter provides a really good insight into how these social and environmental factors can impact the supply chain for raw materials.

Another aspect considered in Chapter 3 is the processing of the mined ores, as both (fresh) water and energy are needed to process the materials. However, the availability of water is considered in some countries to be one of the limiting factors for the future supply of some natural materials. Some areas containing arid or semi-arid regions are using salt water but converting it into fresh water consumes large amounts of energy during the process. As salt water is found in numerous locations, the question surrounding the sufficient supply of water for mining and processing activities can be turned into a question regarding the supply of sustainable and sufficient energy. Research completed by the consortium has determined the energy needed during the mining and processing of the ores (along with social and political issues) is the most critical factor affecting the supply of raw materials. Therefore, with respect to the raw material requirements for ‘green technologies’ a sustainable approach to the water and energy supply for mineral exploitation is a central challenge for the future and could potentially mean a transition to renewable energy technologies.

It is important to note that so far, we have only discussed primary resources of raw materials, sourced by the mining of mineral resources from the geosphere, the portion that includes the Earth’s interior, rocks and minerals, landforms and the processes that shape the Earth’s surface. This chapter opens up the topic of recycling from the technosphere (all of the technological objects manufactured by humans) to supplement supplies. The technosphere still needs much development to reach its potential, it is unlikely to meet the full demands as they are always increasing. Germany has set up the German Mineral Resources Agency (DERA) to monitor critical raw materials and regularly report on the availability of natural resources that are critical to the German industry. The UK is also monitoring critical raw materials with the UK Government asking for reports from the Foresight Future of Manufacturing Project (reports available online). Industries need to secure their supply of raw materials, react to warning signals when necessary and outline alternative strategies which could involve substitution of raw materials (direct substitution) or technologies (technological substitution). The German government plays an active role in concluding trade agreements, subsidising research and financial guarantees. It becomes clear through reading Chapter 3 that the supply of raw materials is vital but has many complicated issues that need to be considered. Though we often deliberate the here and now, we also need to consider the future and how the supply will change in terms of new technologies developed and availability (resources and geopotential). Increases in the efficiency of exploration, production and processing all lead to an enhanced availability of natural resources. Areas that have been identified in this book that need further technical advances are penetration depths, precision and surface coverage of exploitation.

It was concluded that the geosphere and technosphere have sufficient potential to meet an increasing demand for resources until 2050. This is conditional on functioning markets, efficient and sustainable infrastructures as well as research and development.

**Current Status of Natural Resources – An Overview**

Germany is an important mining country and is the largest global producer of lignite (brown coal) and the fifth main producer of potash in the world. Chapter 4 looks at the supply of raw materials within Germany. It produces enough sand, gravel, kaolin and gypsum for its home market, but it is reliant...
on imports of mined metallic mineral resources. These are primarily chromite sourced from South Africa and Turkey, iron ores from Brazil, Canada and Sweden, germanium from China, Russia and the USA along with copper ores from Peru, Chile, Argentina and Brazil.

Chapter 4 also covers the use and demand for fossil fuels within Germany and how the needs will change as renewable energy becomes more prevalent. Energy storage is a key infrastructure that needs to be developed in parallel with renewable energy due to the fluctuating supply (for example solar and wind). Until then fossil fuels will continue to play a key role in Germany’s energy supply. Biomass is another source that is utilised within Germany though it is currently only required for non-energy uses. The waste produced from the biomass has the potential to be used for energy generation. Bioenergy has the lowest energy efficiency compared to other renewable sources, contributing less to the reduction of greenhouse gases compared to wind and solar energy. The higher energy density and storability though are advantageous for its use either in transport or generating electricity during periods of calm winds or low solar radiation. The information in this chapter is focused around what Germany’s needs are and though resources in the UK may differ, it gives a good insight into how the availability of different resources could affect the development of renewable energy sources in developed countries.

The Raw Material Requirements for Energy Systems

In a previous chapter the criticality of raw materials was discussed in respect to its supply, derived from the ratio of demand and supply of the raw material. By designating a raw material critical, precautionary measures can be implemented to ensure a reliable supply, avoiding irregularities and price peaks.

Chapter 5 looks at the criticality ratio of raw materials in greater detail. Many metals (platinum group metals, indium, niobium, tungsten, gallium, Ge and tellurium) are classified as critical in their supply. The information from criticality studies can be used by governments, businesses and society to implement measures to ensure the supply of these raw materials. Current indications predict that lithium and Cu have no significant problems in their supply for the ‘energy systems of the future’.

Summary and Opinions

The book description puts the target audience as “everyone interested in the future raw material supply”, but the overall text contains a lot of technical information that can be difficult to follow and retain due to the structure of the sentences. This is due to the translation of the text from German to English, creating long and complicated sentences, taking longer to absorb the information in a section. The summaries at the end of some of the sub-chapters are fantastic for reviewing the information and highlighting the key facts. These provide a good outline for each chapter and are a good point to start before actually going into the details of the chapter.

This book highlights what a vast array of information is needed to piece together the information regarding the supply, demand and use of raw materials for the future. The consortium that came together to produce the research for this book have combined their knowledge to understand how the markets could change, what could affect them and the predictions that can be made.

Reference


The Reviewer

Jenny Mash received her PhD from the University of Surrey, UK, in the field of electrical energy storage, focusing on creating electrodes for use in supercapacitors. Since joining Johnson Matthey in 2012 she has gained experience working on a range of technologies in this field concentrating on polymer gel electrolytes, ink formulation, scale-up of electrodes and electrochemical analysis of electrodes for batteries and Li-ion capacitors. Currently Jenny works as a Senior Research Scientist in the Recycling and Separations Technology group, developing process models for battery recycling.
Johnson Matthey Highlights

A selection of recent publications by Johnson Matthey R&D staff and collaborators

Flat and Efficient HCNW and CNN Pincer Ruthenium Catalysts for Carbonyl Compound Reduction
RuCl₃·xH₂O, [RuCl₂(CO)₂]ₙ, [RuCl₂(PPh₃)₂(dmfc)(CO)], [Ru(OAc)₂(PPh₃)₂(CO)] and cis-[RuCl(CNN)(PPh₃)]₂ precursors were used to synthesise bidentate HCNW trans-[RuX₂(HCNW)(L)(CO)] (X = Cl, OAc) and pincer CNN [RuCl(CNN)(L)(CO)] (HCNW = Hamtp, Hambq, HambqPh; L = CO, PPh₃) carbonyl complexes. In the presence of phosphine (PPh₃ or PCy₃), the monocarbonyl complexes and dicarbonyl derivatives were shown to catalyse the transfer hydrogenation (TH) of acetophenone in 2-propanol at reflux and the TH of carbonyl compounds (including bulky ketones and β-unsaturated aldehydes).

Technical Considerations for Scale-Up of Imine-Reductase-Catalyzed Reductive Amination: A Case Study
Imine reductases (IREDS) can be used as biocatalysts for the synthesis of various cyclic and acyclic amines. The development and scale-up of such reactions was considered based on the reductive amination of cyclohexanone with cyclopropylamine. Various reaction parameters were studied using a design of experiments approach, which identified enzyme stability as the limiting factor. Kinetic studies demonstrated that IRED-33 was the most stable enzyme for the reaction. In an 8 h period, and under optimal reaction conditions, 100% conversion to the desired amine was achieved from the reaction of cyclohexanone and cyclopropylamine at 750 mM concentration.

Accurate 3D Characterization of Catalytic Bodies Surface by Scanning Electron Microscopy
Industrial catalysis often uses catalytic bodies of millimetric dimensions. The chemical and spatial relations of the exposed surface of the catalytic device are affected by the raw nanocatalyst engineering process. It is therefore vital to understand the heterogeneities of catalytic device surfaces to improve their synthesis. Three-dimensional and high resolution physico-chemical characterisation was performed on the surface of commercial water gas shift catalyst bodies using a combination of photogrammetry, scanning electron microscopy and X-ray spectroscopy. The measurements observed from these methods were shown to be reliable, accurate and precise.

Slurry Loop Tubular Membrane Reactor for the Catalysed Aerobic Oxidation of Benzyl Alcohol
A novel slurry loop reactor was designed and implemented for the aerobic oxidation of benzyl alcohol using a 1 wt% Au-Pd/TiO₂ powdered catalyst. Safe and controlled oxygen delivery was achieved with the incorporation of a tubular membrane. In comparison to a conventional autoclave reactor, the slurry loop reactor demonstrated similar oxidation turnover frequency and benzaldehyde selectivity (20,000–25,000 h⁻¹ and 70%, respectively). To allow for continuous operation, a crossflow filter was inserted inside the loop to prevent the catalyst from exiting the reactor. Undertaking continuous reactions showed that increasing the external oxygen pressure or decreasing the reaction temperature increased
benzaldehyde selectivity. Applications that are limited by gaseous reactant availability, use a powder catalyst and require safe operation could benefit from the slurry loop reactor.

Modelling Reaction and Diffusion in a Wax-Filled Hollow Cylindrical Pellet of Fischer Tropsch Catalyst

A pseudo-isothermal, steady-state, two-dimensional (2D) model was investigated for the Fischer-Tropsch (FT) reaction for solid and hollow cylindrical cobalt-based catalyst pellets. The Co-based catalyst was considered at conditions where liquid hydrocarbons accumulate in the pores. Comparisons were made with sphere and slab models. With regard to effectiveness factor, slab and sphere values were exceeded between the Thiele moduli range of 0.75–1.15. However, with the FT chain growth parameter, the values were lower than slab and sphere geometry. Therefore, hollow cylinders under these conditions demonstrated the greatest selectivity towards methane.

Opportunities and Challenges for Catalysis in Carbon Dioxide Utilization

In carbon dioxide (CO₂) utilisation processes, CO₂ is either used directly or converted into more valuable products. Such processes will be vital for reducing CO₂ emissions in our atmosphere. The successful conversion of CO₂ to value-added products will be heavily reliant on catalysis. This paper provides a review of the biological and chemical systems for CO₂ utilisation, along with the specific and more general challenges that will be presented. Comparisons are drawn between various methods of CO₂ conversion, for instance homogeneous vs. heterogeneous catalysis and photosynthetic vs. nonphotosynthetic biological conversion. Issues with CO₂ conversion are also identified, which will need to be addressed by the technology.

Toward Stable Electrode/Electrolyte Interface of P2-Layered Oxide for Rechargeable Na-Ion Batteries

P2-Na₂/3Mn₀.₈Fe₀.₁Ti₀.₁O₂ layered oxide has potential as a cathode material for rechargeable Na-ion batteries (NIBs). An optimised ionic liquid (IL)-based electrolyte was used to evaluate the electrochemical properties of P2-Na₂/3Mn₀.₈Fe₀.₁Ti₀.₁O₂. In comparison to a carbonate-based electrolyte, the IL-based electrolyte demonstrated better electrochemical performance at room temperature. Cycling stability was also particularly strong, with a 97% capacity retention after 100 deep cycles. Scanning electron microscopy and X-ray photoelectron spectroscopy were employed to study the electrode/electrolyte interface in both systems. The IL-based system had a thinner, more stable and homogenous interface layer. Therefore, such systems could lead to longer-lasting and safer NIBs.

Electronic and Geometric Structures of Rechargeable Lithium Manganese Sulfate Li₂Mn(SO₄)₂ Cathode

The synthesis and characterisation of Li₂Mn(SO₄)₂ (LMS) (Figure 1), a potential energy storage material, is described over one electrochemical cycle. LMS was synthesised by ball milling MnSO₄·H₂O and Li₂SO₄·H₂O. A combination of ex situ X-ray diffraction, X-ray photoelectron spectroscopy and X-ray absorption spectroscopy were used to characterise LMS. X-ray photoelectron spectroscopy analysis demonstrated changes in the oxidation state of Mn, whereas X-ray absorption spectroscopy analysis suggested minimal changes to the oxidation state of Mn and S ions during charge-discharge cycles. Dominance of electrochemical reactions at the surface of the LMS particles, rather than in the bulk, could explain the difference in the results during cycling.

Extracting Structural Information of Au Colloids at Ultra-Dilute Concentrations: Identification of Growth During Nanoparticle Immobilization

Using sol-immobilisation to achieve supported metal nanoparticles (NPs) ensures a high degree of control of the metal particle size and yields a narrow particle size distribution. In this study, state of the art beamlines and X-ray absorption fine structure techniques were used to provide structural

Fig. 1. Reprinted with permission from D. Gupta et al., ACS Omega, 2019, 4, (7), 11338. Copyright (2019) American Chemical Society. Further permissions related to this material should be directed to the ACS
information on nano-sized colloidal Au solutions at μM concentration. By adjusting the temperature of reduction, it was possible to accurately tune the size of Au colloids. It was also demonstrated that Au concentration had little effect on the size of colloidal Au NPs in solution. A significant growth in Au particle size was attributed to the immobilisation step. By understanding the primary steps in sol-immobilisation, the optimisation of materials for catalytic application can be improved.

Ultra-Smooth and Space-Filling Mineral Films Generated via Particle Accretion Processes

Nonclassical crystallisation is driven by nanoparticle self-organisation. Therefore, it tends to yield materials with pronounced porosity and roughness. In this study, a bio-inspired nonclassical mineralisation approach was taken, via magnesium-doped polymer-induced liquid precursors, to generate ultra-smooth and dense calcium carbonate films. The films featured a roughness of 0.285 nm, which is uncharacteristically low for minerals generated via nonclassical pathways. The research provides an insight into the role of magnesium in biomineralisation of calcareus species. It also describes a concept for lifting key limitations of nonclassical mineralisation pathways.

Improvements to the Production of ZIF-94; A Case Study in MOF Scale-Up

Metal organic frameworks (MOFs) have shown remarkable promise at the laboratory scale. Large-scale production is essential for their successful commercialisation. This study demonstrates improvements in the production of ZIF-94 from ~1 g laboratory preparation to a scalable procedure. Conditions for the ZIF-94 synthesis included atmospheric pressure and room temperature. Unlike current synthesis routes, dimethylformamide was not used as a solvent. The weight percent of solids from this method was higher than previously reported synthetic routes, at 18 wt%. A large scale (60 g) production of the framework was produced to highlight the robustness of the derived methodology. Overall, ZIF-94 production demonstrated improved concentration, improved CO₂ uptake, maintained nano-morphology and reduced costs.

Impact of Carbon Support Corrosion on Performance Losses in Polymer Electrolyte Membrane Fuel Cells

Membrane electrode assemblies (MEAs) were cycled between 1−1.5 V in order to study the effect of degradation on oxygen transport. Focused ion beam-scanning electron microscope (FIB-SEM) tomography was used at various ageing states to analyse electrode structure. Results demonstrated that electrode structure (porosity, thickness and diffusivity) changed over 1000 cycles. The pressure independent resistance increased from 24 sm⁻¹ to 41 sm⁻¹. 50% of this increase was attributed to an increased local mass transport resistance and 44% from a change in the wetting behaviour. 6% of the increase remains unexplained.
Circular economy (CE) thinking has emerged as a route to sustainable manufacture, with related cradle-to-cradle implications requiring implementation from the design stage. The challenge lies in moving manufacturing environments away from the traditional linear economy paradigm, where materials, energy and water have often been designed to move out of the system and into receivership of waste management bodies after use. Recent applications of industrial digital technologies (IDTs: for example internet of things, data-driven modelling, cyber-physical systems, cloud manufacturing, cognitive computing) to manufacturing may be instrumental in transforming manufacturing from linear to circular. However, although IDTs and CE have been the focus of intensive research, there is currently limited research exploring the relationship between IDTs and the CE and how the former may drive the implementation of CE. This article aims to close the knowledge gap by exploring how an IDT (data-driven modelling) may facilitate and advance CE principles within process manufacturing systems, specifically waste valorisation and process resilience. These applications are then demonstrated through two real-world manufacturing case studies: (a) minimising resource consumption of industrial cleaning processes and (b) transforming wastewater treatment plants (WWTPs) into manufacturing centres.

Introduction
Manufacturing drives the economies of all countries from low to high incomes; contributing 16% to global gross domestic product and 23% of global employment in 2017 (1). Manufacturing is split into two branches: discrete manufacturing (automobiles, computers and electronics, textiles) and process manufacturing (chemicals, food and drink, pharmaceutical, fast-moving consumer goods (FMCG)). The difference is that discrete manufacturing is the cutting and assembly of a bill of materials into a final distinct product (2), whereas process manufacturing is the thermal, chemical or biochemical conversion of resources into products, byproducts and waste streams (3). Both share the core value that their products and processes must be profitable to remain in business (4). However, there is mounting pressure for businesses to become not just economically sustainable but also environmentally sustainable.
A key goal of sustainable manufacturing is to conserve energy and natural resources (5). The methods of achieving sustainable manufacturing
differ between discrete and process manufacturing. Discrete manufacturers are largely limited to minimising resource consumption and redesigning their products to use sustainable resources where possible (6). Process manufacturers are often able to keep the characteristics of their products the same but redesign their systems to use alternative sustainable feedstocks (7). Despite progress made by manufacturers, more needs to be done to meet demands of a growing population. In 2017, the European Union (EU) expanded its list of critical raw materials (CRM) to 27. These are defined as materials considered to be of high importance to the EU economy and of high risk to their supply (8). CE thinking has emerged as a means of increasing the resilience of manufacturing to disruptions in the supply of resources.

The UK-based Waste and Resources Action Programme (WRAP) charity defines the CE as “an alternative to a traditional linear economy (make, use, dispose) in which we keep resources in use for as long as possible, extract the maximum value from them whilst in use, then recover and regenerate products and materials at the end of each service life” (9). The application of CE thinking to process manufacturing requires deeper consideration than discrete manufacturing, where it is simple to visualise a discrete product being reused, repaired and recycled (such as fixing a kettle). This school of thought does not lend itself to some process manufacturing products; for example, it is not possible to reuse, repair or recycle a pharmaceutical drug once consumed. However, by expanding the system to include waste produced during manufacturing (i.e. capture pharmaceuticals in waste or water streams and recover for use) and waste from the consumer (in this example human waste entering wastewater systems) it is possible to recapture the resource into the economy through waste recovery and valorisation. This also offers opportunity to increase profitability, in addition to reducing environmental pollution.

The application of emerging IDTs to manufacturing (sometimes referred to as Industry 4.0) to support the implementation of the CE has strong potential (10). However, a keyword search on the Web of Science database returns only 29 documents for both “circular economy” and “Industry 4.0”, compared to 4138 and 4031 when the keywords are searched independently. This article aims to close the knowledge gap by exploring how IDTs may support CE principles within process manufacturing systems, specifically waste valorisation and process resilience.

Two process manufacturing case studies are evaluated within the field of CE. The first case study focuses on applications of CE to support waste valorisation within waste and wastewater management. For process manufacturing, 50–100% of the starting materials (and hence resources used in that system) are removed from the system via the wastewater. The wastewater and resources within then enter waste management bodies such as solid waste or WWTPs, or depending on the country and regulations (that may or may not be evident or enforced) may be released directly to the natural environment (11). Recovering water, energy and nutrients is an established application of CE to WWTPs (12) and readers are referred elsewhere (13) for a review of current innovations within WWTPs. However, the manufacturing environment from the CE perspective offers more inclusive considerations. Here innovative thinking coupled with new technologies enables process manufacturing plants to adapt and emerge, switching priorities from treating waste and water for reuse to manufacturing products from waste streams. The second case study demonstrates how IDTs may increase the resilience of FMCG industries and reduce resource consumption. Recent literature has demonstrated some innovative applications of IDTs to FMCG (14, 15). This case study aims to demonstrate how these technologies may be utilised within the context of CE.

**Waste Valorisation Between Manufacturing Systems**

There is a consensus among researchers that it is not possible to reach a fully CE, as the process of recycling will also always create waste and side products due to increasing entropy (16). Instead, the goal is to identify resources from renewable sources and to minimise the spent resource leaving the system (17). Process manufacturing systems can take this further as their waste can contain valuable material available to use as is or as a building block for a related process manufacturing environment. This is known as the cradle-to-cradle concept, where waste is both recycled and utilised as a raw material (18). Applying this concept expands the traditional CE model from a singular circular system to a series of connected circular systems, where one system’s waste is another’s resource. This reimagining of the CE concept is shown in **Figure 1**.

The challenge of brokering relationships between manufacturers to form innovative collaborations that find ways to utilise waste from one as a
raw material for another is known as industrial symbiosis (19–21). There are examples of support networks for industrial symbiosis, such as the National Industrial Symbiosis Programme, UK (22); Cleantech Östergötland, Sweden (23) and Kalundborg Symbiosis, Denmark (24). However, more needs to be done to make industrial symbiosis a wide-spread reality (25). There is an opportunity to utilise recent data-driven analysis and modelling advances to drive the implementation of industrial symbiosis (10). One such application is the development of data-driven models to describe manufacturing systems and enable intelligent decision-making on cloud platforms like Sharebox (a platform for physical resource sharing) (3, 26). Data-driven models can identify relationships between the system state variables (input and output) to inform on the system and make predictions on key process variables (for instance, product yield and quality) (27). By sharing and modelling a system’s data, a data-driven model may evaluate the economic feasibility and environmental impact of utilising that waste as a resource. The model could further be used to evaluate multiple different systems to select the most sustainable valorisation route. For example, brewers’ spent grain has multiple valorisation routes (animal and human food production, paper production, adsorbent material, enzyme production, energy source) (28). The different industrial processes to valorise the spent gains are impacted by the spent grains’ characteristics (physical properties, microbial and chemical composition) (29). A data-driven model may evaluate which valorisation route is the most sustainable dependant on the spent grains’ characteristics.

Traditionally waste and WWTPs were the last stage of a product’s lifecycle, either treating the waste before releasing it to the surrounding environment, or with some limited reuse in system (such as heat production). Nowadays, most WWTPs recover at least some of the energy trapped in the waste and water streams and the next generation of WWTPs are targeting energy neutrality and recovery of nutrients (11). A Severn Trent Water WWTP at Stoke Bardolph, UK, illustrates the innovative work already ongoing by process manufacturers to recapture phosphorus and energy back into the economy (30). P is on the EU’s 27 CRM list and although fairly common is included because of its widespread use for crop fertilisers risking future supply. Globally, 20% of the manufactured P is contained within domestic wastewater (11) and if recovered could limit the depletion of phosphate rock that is not renewable (31). The Stoke Bardolph site uses two PHOSPAQ™ reactors (developed by Dutch company Paques BV) that recover approximately 736 tonne year⁻¹ of phosphorous in the liquor dewatered from the sludge from municipal sewage treatment (30). Also installed on the site is an ANAMMOX® reactor and a BIOPAQ® Upflow Anaerobic Sludge Blanket (UASB), which recover ammonia and generate biogas respectively. This is then used for the combined heat and power engines, contributing 7% to the site’s energy use (30). With innovative thinking, coupled with new technologies, future WWTPs could take this further, so they are not only recovering resources but also manufacturing products onsite, Figure 2. The energy and water recovered from the wastewater could be used to support the manufacturing processes, helping to realise a truly CE by reducing the requirement of fresh resources, Figure 2. There is the potential to generate a wide range of products from wastewaters including: biofuels, biohydrogen, biopolymers, single-cell protein, fertiliser, cellulose and alginate acid as well as nutrients and metals recovery (11, 32). However, there is still some way to go before these circular thinking technologies can be deployed, as the technology readiness levels (TRL) for most are below TRL5 (11). TRLs measure the maturity of technology during the stages of its development between basic principles (TRL1) and commercialised operating product (TRL10) (33). One project aiming to achieve this is the NextGen initiative, funded by the EU (34). NextGen aims to demonstrate innovative technological, business and governance solutions for water in the CE, in
ten high-profile, large-scale, demonstration cases across Europe.

**Process Resilience Across Different Manufacturing Environments**

Process manufacturers consume an extensive amount of resources during production processes. For example, the processing industries use 20% of the total global freshwater reserves during production (35). Towards the goal of sustainable resource use, the first steps are to investigate substituting raw materials for sustainable alternatives and to increase the efficiency of manufacturing processes to reduce the resources wasted during production. This falls under the field of ‘process intensification’, which is a chemical and process design approach that leads to substantially smaller, cleaner, safer and more energy-efficient processes (36). Process manufacturing systems are subject to variability throughout the system, including variations in feedstock characteristics and supply, unit operation process conditions and the waste produced by the system. This variability results in wasted resources, as manufacturers over-design their systems to limit the impact variability has on product quality and yield (37), and increases the complexity in process intensification attempts (38). As manufacturers move away from non-renewable sources towards renewable feedstocks this will become an even greater challenge for engineers (39). Previously, process manufacturing plants have been over-designed in an attempt to capture the variability within the boundaries of the plant’s system (40).

Recently there have been advances in the application of data-driven modelling to better understand and optimise process manufacturing systems (41, 42). By modelling historic data, it was possible to identify and understand the effect of the variables that strongly affect the system (42). The model can then be used to make predictions on how these variables can be manipulated to reach the model’s goal, defined by the manufacturer. Currently, process manufacturers collect a large amount of data from process control systems that is not fully utilised and often only used for after-the-event analysis (43). There is an opportunity to develop data-driven models from this data to investigate the cause of resource waste within the systems and ensure this waste is designed out of future systems. For example, in the biopharmaceutical industry yields can vary from 50% to 100% for no immediately discernible reason (42). Sadati et al. were able to develop a data-driven model from historic data that identified the control variables resulting in fluctuations in yield (42). Data-driven models can also improve the development of affordable sensors to monitor systems that have previously been economically unfeasible to monitor. This is particularly true for the food and drink industry that is characterised by a large number of small and medium enterprises (SMEs) who face small profit margins and have limited resources to utilise new IDTs (44). For example, clean-in-place (CIP) systems (a method of cleaning the interior surfaces of pipes and process equipment without disassembly) use excessive amounts of water, chemicals and time. Cleaning is essential to ensure the equipment remains hygienic but inefficient in terms of resource use as systems are always designed to clean the materials which cause the worst fouling to the equipment (45). If manufacturers were able to model and predict the fouling behaviour of each product it would reduce the amount by which the CIP systems are over-designed, resulting in a saving of resources. An example of a sensor and data-driven model system used to reduce resource use during industrial equipment cleaning processes is presented in Figure 3. A data-driven model was developed to predict the point at which cleaning

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**Fig. 2.** Innovative WWTPs case study. Moving beyond the traditional concept of treating water so it is fit for purpose e.g. for release to the aqueous environment. Moving towards treatment plants of all sizes powered by the renewable bioenergy recovered from the waste or water and additional products where resources are recovered.
was achieved by modelling measurements from an affordable, non-intrusive ultrasonic sensor.

When aiming for sustainable manufacturing it is important to recognise that what is sustainable in one environment may not be sustainable for another. Different geographical regions and industries face different regulations and have access to different resources. The EU’s rare earth minerals are depleted and there is a heavy reliance on imports, as reflected in the EU’s list of CRM (8). Regions that still contain plentiful mineral reserves may face different challenges such as water stress (46). Data-driven modelling for dynamic forecasting of a range of applications has already been tested in a variety of fields (47). In the future, it may be possible for a manufacturer to model and forecast the availability and variability of the supply of resources. This will enable intelligent decision making to identify and implement the most sustainable manufacturing route dependent on available resources. By recovering, reusing, recycling and valorising waste resources it will further increase the resilience of manufacturing systems from disruptions in the supply chain.

**Final Remarks**

During the 20th Century, our manufacturing systems were driven by economic incentives to expand the production of goods and services, with little to no regard to the environmental impacts this caused (48). In the past couple of decades there has been a recognition by the international community that this is unsustainable and manufacturers have been pressured to introduce sustainable strategies. However, the progress made has not been sufficient and the resources required to support the global population now exceed those available (49). This article has offered a brief overview of the applications of data-driven models (a key IDT) to support the CE principles of waste valorisation and process resilience. Data-driven modelling applications for analysis, decision making and forecasting were presented in the context of two process manufacturing case studies. A gap currently exists between the research fields of CE and Industry 4.0, as demonstrated by the limited number of joint publications between these fields. Therefore, there is great potential for research demonstrating the application of further IDTs (for example internet of things, cyber-physical systems, cloud manufacturing, cognitive computing) to drive the CE.

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