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Concept Paper

Circularity in Practice: Review of Main Current Approaches and Strategic Propositions for an Efficient Circular Economy of Materials

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Abstract: This paper aims to summarize, propose, and discuss existing or emerging strategies to shift towards a circular economy of materials. To clarify the landscape of existing circular practices, a new spectrum is proposed, from product-based strategies, where entire products go through several life cycles without being reprocessed, to material-based approaches, extracting, recycling, and reprocessing materials from the waste flow. As refillable packaging does not lose any functionality or value, when re-used through many life cycles, product-based strategies are globally extremely efficient and must be promoted. It appears however that their implementation is only possible at the scale of individual products such as packaging containers, relying on the cooperation of involved companies and consumers. It appears more and more urgent to focus as well on a more systematic and flexible material-oriented scheme. The example of circular glass recycling is a success in many countries, and technologies become nowadays available to extend such practices to many other materials, such as rigid plastics. An ideal would be to aim at an economy of materials that would imitate the continuous material cycle of the biosphere. Technological and business strategies are presented and discussed, aiming at a relevant impact on circularity.

Keywords: circularity; circular economy; recycling; sorting; sustainable development; industrial ecology

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1. Introduction

The growing pro capita consumption of materials, a growing world population, along with the currently prevailing model of production and disposal are challenging the sustainability of our societies [1,2]. The materials that we extract from nature exist in a limited amount as economically attractive resources, and are regenerated at a much lower rate than the current extraction. Therefore the virgin stocks of several key materials appear inadequate to sustain the modern "developed world" quality of life for all earth's peoples under contemporary technology [3].

On the other hand, emissions during the production of materials and disposal at the end of a product's life are sources of pollution in many different ways, including for instance the often quoted rising concentration of microplastics in the oceans and its consequences [4]. A final threat is the increasing number of geopolitical conflicts driven by the economic gain through importing raw materials from a minor number of large-scale reservoirs [5,6].

As we face those challenges, nature appears to be the only successful known system with an endless flow of resources transforming continuously from raw materials to products and vice versa, all of this with acceptable emissions, without depletion and strictly using locally available materials. That success inspired the concepts of Industrial Ecology (IE) and circularity, as answers to the lack of sustainability of our current linear system (extraction, use, disposal) [7,8]. IE has examined what can be learned from nature in a literal sense, such as when artificially creating materials or mimicking processes found in nature on an industrial scale or when applying solutions found in nature to product design [9].

As the concept of circularity is finding echo [10] and first practical applications arise, it is clear that mankind will not use the concept of circularity in exactly the way that nature does, i.e., without the planning, political supervision, regulation, or large-scale organization that are key to our societies. Advanced societies will be likely to require the concept of circularity to be caught in contracts and negotiations, and ask for an efficient optimization towards the goals of human society within a short time frame. This presupposes a measurement of circularity, that could reshape the way we think about production and consumption. Several attempts have been made to define a metric for circularity [11,12] to allow the monitoring of new processes emerging from the concept. Given the myriad ways in which the businesses of the world are interconnected, it would be preferable to have a broad consensus about the basis of such circularity assessment. This is the focus of Section 2 of this paper.

Another issue related to planned versus not-planned processes is that nature's circularity focuses almost exclusively on recycling materials and designing new tissues for the re-use of recycled materials. Looking at the bio-cycle almost always means that nature breaks down materials to a low level, even to chemical/molecular/atomic levels. The vast majority of the bio-cycle materials are recycled at the molecular level and sometimes even below it: to the atomic level before new materials are built up again. Standardization of biochemical building blocks like amino acids and nucleotides arrives through the driver to design with available recycled materials and not through regulatory organizations. There is in nature little design *for* recycling, i.e., living tissue is seldom, if at all, designed to facilitate later recycling or re-use. The planned, regulated, and supervised nature of human society allows a much more important role for design for recycling. Therefore a very interesting question is what will be the relative importance of either methodology or route: a circular economy of materials, in which producing waste is avoided as much as possible, and raw materials are primarily recovered from goods reaching the end of their previous use, or, a circular economy of products, in which the complete cycle of a product, from design to use to recycling, is being planned and regulated.

Below, a short review of the main concepts will be given. In the subsequent sections, the state of the art and trends of the three building blocks of circular technology are illustrated through examples from the authors' institute: the recycling of end-of-life products into raw materials, the design of products for use of recycled materials, and, the design of products so as to facilitate their recycling. These three building blocks can be applied to any methodology between two extremes.

The first extreme is to consider circularity at a product level, by planning its entire life cycle. A product must then be designed in such a way so that its recycling, in a broad meaning, will take minimal cost and energy, while often leading to energy-efficient life cycles, this approach goes beyond purely technological issues, and involves new policy, design, business cases, logistics, and sometimes social behavior. It is clearly applicable to simple products such as returnable glass bottles, of which the cycle time is short with respect to the rate of innovation in functionality and design.

The planned approach aims to design a complete product cycle from the start. It is what may be called design for reuse, design for dismantling, design for remanufacturing, or design for recycling. It means that from the start, the target is to design a completely new product cycle. Examples of this approach are companies that make packaging that goes around many cycles (e.g., Pieter Pot [13]) or detergent or dairy producers that place facilities within retailers where customers can refill their plastic or glass containers. This approach is attracting attention from many researchers worldwide. However, at this moment, it is not possible to state to what extent it is possible to plan the life cycle of complex and long-lived products. One challenge is also to deal with objects for which functionality and design innovate considerably during a single use cycle, for example batteries or nuclear plants. Examples are discussed in Section 3 of this paper.

The second extreme is inspired by the material flow in the biosphere: everything that loses its functionality is, one way or another, broken down to a level that can be reprocessed into something new: the recycling happens at the material level. Most of today's industrial recycling follows this way, and the goal is to adapt technologically to society and its production to be able to provide as many new raw materials as possible from its waste. The success of this approach will depend on its ability to deal with a huge range of complex materials in waste while remaining energy- and cost-efficient in their separation, extraction, and reprocessing. Section 4 of this paper will focus on the concepts of data-driven recycling and demand-driven recycling as novel methodologies to bring the recycling industry to meet this challenge. In this extreme scenario, recyclers can be considered as raw materials extractors and act the same way as the present primary raw material industry. Today's waste-driven recycling strategy, focusing on identifying and extracting easily tradable commodities from the waste material, is replaced by demand-driven recycling that allows a new industry sector to offer an alternative to the primary raw material industry. This route implies a major change of business organization and technology to enable recyclers to deal with waste materials and end-users in all its complexity.

As a society, the questions we should try to address are: (1) Which of the two approaches is likely to be widely implemented? (2) What is the share of all raw materials that can be saved by implementing the two strategies in the short term and with a minor impact on our societies?

Through this spectrum, this paper aims to review some examples and strategies that aim towards circularity, to analyze the challenges they bring up and propose some clear, pragmatic directions to researchers, industries, designers, and policy-makers involved in that big economic shift.

It seems important first to remind first, in the following section, the basic concepts and metrics discussed so far by researchers, supporters, and policy-makers to define circularity.

2. Metrics for Circularity

Although the Circular Economy (CE) approach contrasts with the mindset embedded in most current industrial operations where even the terminology (value chain, supply chain, end-user) expresses a linear view, several benefits may arise from the shift to the Circular Economy model and to a more resource-efficient path. The material saving potential arising from the transition to a CE model and to a more resource-efficient path is estimated to be EUR 500 billion per year for the European industry, considering all materials [14]. The job creation potential of remanufacturing and recycling in Europe is estimated at one million [15]. From the strategic point of view, the benefits of the CE approach arise from the reduced risk of supply disruption and price volatility as well as from the huge potential for innovation related to new technologies (needed to increase resource productivity, material substitution, waste management, and recycling), improvements of the forward and reverse cycles (optimization of the supply chain and logistics), and new and creative business models [16].

Moreover, the adoption of CE practices appears as a timely, relevant, and practical option to meet the goals of Sustainable Development (SD) [17]. In fact, Schroeder et al. (2019) showed that the implementation of CE approaches can be applied as a "toolbox" for achieving a sizeable number of SD targets [18]. Accordingly, the CE paradigm is being extensively explored by institutions as a possible path to increase the sustainability of our economic system (Elia et al., 2017) [19]. To some, e.g., Linder et al. (2017), the ultimate goal of a CE is an SD [20]. Anyway, it is clear that both concepts need appropriate means of measurement and evaluation to make good progress. That is why the measurement of circularity is gaining much attention among the academic community.

The main questions raised by researchers are (Saidani et al., 2019) [17]:

1. How to measure the progress of the transition towards a CE? [21];
2. How should we measure its performance since its objectives (e.g., reduce, reuse, recycle) are substantially different from those in the traditional linear economy? [22];
3. How is circularity measured in businesses and economies? [23];

4. How should product-level circularity be measured? [20];
5. Is it possible to develop indicators that are simple, intuitive, robust, and aligned with policy? [16].

According to the EASAC (2015), companies may lack the information, confidence, and capacity to move to CE solutions due to a lack of (i) indicators and targets, (ii) awareness on alternative circular options and economic benefits, and (iii) the existence of skills gaps in the workforce and lack of CE programs at all levels of education (e.g., in design, engineering, business schools) [22].

Therefore, it is now commonly acknowledged that to promote CE, the introduction of monitoring and evaluation tools like indicators to measure and quantify this progress becomes essential [16,24–28].

The European Commission has also recognized this need for circularity indicators through its action plan for the CE (EC, 2015a) stating that "to assess progress towards a more circular economy and the effectiveness of action at EU and national level, it is important to have a set of reliable indicators" [29].

Several academics describe the importance of indicators for developing the circularity to the operational level. In fact, advancing the discussion of the CE to a higher level requires reaching a shared understanding and common language [23,30]. For instance, assessment methods such as the use of indicators can play a key role in generating a deeper understanding and integration of the CE, e.g., in helping industrial practitioners set suitable circular economy targets, and to effectively measure the progress towards the objectives linked to the CE-related strategies [17].

Having clarified that indicators are considered essential to measure (and implement) CE, it is remarkable that there are several definitions of what an indicator is [31–35]. According to OECD (2014), an indicator is defined as "a quantitative or qualitative factor or variable that provides a simple and reliable means to measure achievement, to reflect changes connected to an intervention, or to help assess the performance of a development actor" [32].

An indicator framework entails a collection of indicators that "conveys a broader purpose and significance to the individual indicator and provides a comprehensive picture of some entity" [36]. Therefore, indicators simplify information, can help to reveal complex phenomena, and provide an effective tool for measuring progress and performance.

Indicators have: (a) the ability to summarize, focus and condense the complexity of the dynamic environment to a manageable amount of meaningful knowledge [34], that is to say, the potentiality of relaying complex information in a simplified and useful manner [36]; (b) the capability to communicate, raise public awareness on important issues (e.g., potential environmental impacts), and to (c) indicate whether or not targets will be met [37]. Indicators can also be used as managerial and policy-making instruments to report or pilot activities; define goals, quantitative targets, and track progress; arbitrate potential trade-offs and impact transfers; inform investment choices and guide policy-making; communicate externally; support education and training. Last but not least, according to Wass et al. (2014), indicators contribute to the need for shortcuts and rules of thumb to support decision-making [38].

Due to the common understanding and agreement about the importance of indicators to measure progress and to facilitate the transition towards CE (and SD), many indicators have been proposed so far. A comprehensive analysis of circularity indicators has been carried out by Saidani et al. (2019) [17]. The authors present a list of 55 circularity indicators along with acronyms and sources. The large number of indicators signifies the urgency of consensus in measuring circularity as well as the importance and need of a robust methodology to do so.

One first challenge is the need for quantifying circularity, the following sections aim to reveal the field of possible strategies, through examples from *re-use* and a similar product-based approach to the other extreme of molecular breakdown.

Classification of Approaches

Any way to bring an end-of-life (EoL) product into a new life cycle is a form of recycling. This paper proposes to classify those ways according to the extent of reduction the product has to go through: from no reduction (product-based approach) to reduction to the material or molecular level, thus having to undergo such *unprocessing* to be processed back again into a new product.

Figure 1 illustrates the relationship between circularity (inversely proportional to the degree of innovation for each life cycle), breakdown level (from entire objects to molecular level reduction), and energetic costs. It can be said that on the "Breakdown of End-of-Life product" axis, recycling of complex parts or mono-material parts can be considered as a product-based approach, as they only involve extraction and maintenance of such parts. Re-use of bottles, for instance, is also a form of mono- or bi-material "parts".

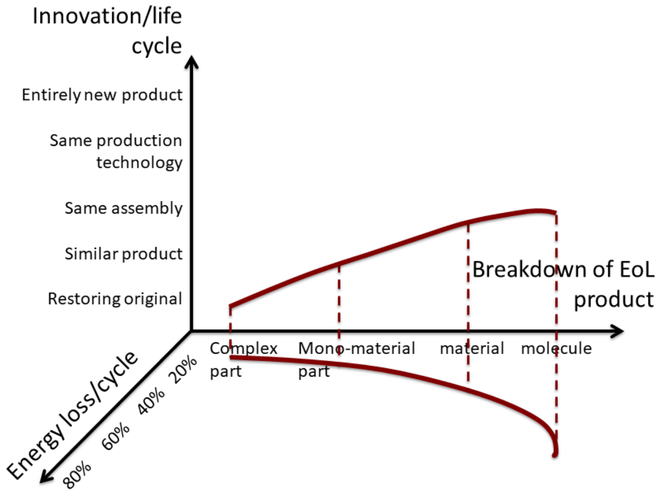

Figure 1. Illustration of the innovation per use cycle and the degree to which the end-of-life (EoL) product needs to be broken down with consequent energy loss.

"Material" or "molecule" level breakdowns represent a material-based approach: an end-of-life product is no longer considered in its functionality, but as containing the raw materials to be reprocessed, either using a similar production technology as for its previous life cycle, or using completely new processes to make a different product.

Again, both these approaches have to face, in different ways, the same challenge: be as circular as possible, i.e., losing as little value as possible during the process, while minimizing its emissions and impact on the environment.

Before giving some examples of both approaches, and analyzing the different challenges they face, Table 1 summarizes their respective definitions with generic examples.

Table 1. Summary of definitions and generic examples of the product-oriented and material-oriented approaches.

Approach:	**Product**	**Material**
Definition:	Products or parts are recollected and re-used as such with only necessary functional maintenance	Objects are considered as a raw resource to be reprocessed
Generic examples, keywords:	Maintenance; product or part re-use; product restoration; container re-filling; extending functionality/capacity; adapting product to new use	Material recovery from complex products; material recovery from waste flows; waste mining; sorting; valorization of ground/shredded material; mechanical recycling; chemical recycling; reprocessing; on-demand sorting and recycling

3. Product-Based Circularity

The simplest approach is to apply principles of circularity at a product level. This is often not called "recycling" but "re-using" the objects as such.

3.1. Concept, Link with Design, Planning

With such an approach, at no moment does a product become waste: its re-introduction in a new life cycle has to be done with minimal effort to recover the functionality (washing, maintenance. . .). The most crucial point is then how the product is designed to allow this, and to make products that are resistant enough to go through several life cycles while keeping the same properties, provided that there is only a minimal maintenance step at the beginning (or end) of each cycle.

This includes the *product* as part of an assembly, as long as it is not reprocessed (i.e., reduced to its materials by a chemical or (thermo)mechanical process). The design of the product is thus crucial to allow its extraction or collection, maintenance, and re-insertion into a new life cycle. Specific planning is thus implied for each product and must not only involve design and manufacturing, but also the customer/user, the logistics of getting back products to recycle it in good conditions and recycling/maintenance/refilling. The responsibility of all involved actors for one product would virtually last forever in a truly circular scheme where the product do not lose value nor functionality through life cycles, provided that the product keeps its purpose while society evolves.

As seen in the following cases, on one hand, product-based approaches demand important specific planning for low flexibility, but on the other hand they can prove to be the most efficient according to emissions and energy use.

3.2. Examples/Case Studies

3.2.1. Container-Deposit (Glass Bottles)

One well-known case is the container-deposit system for beverage containers. The idea is that glass (or sometimes plastic) bottles are returned to a facility (often in the shop that sells the beverage) in exchange for a small amount of money, corresponding to a fraction of the price of the product. The container is then washed and can be refilled with the product to be sold again, even saving the energetic costs of glass recycling.

This old approach has proved in many places to involve the consumers more directly in the circular economy, and the refund they get can be encouraging [39]. Experiences from the 1980s already showed benefits in terms of waste reduction, energy savings, and job creation [40]. It was however also criticized for the heavy legal framing, planning, and the difficulties for the industrial sector to adapt to these methods wherever they are imposed by law.

A more recent review was carried out by Zhou et al., considering several container-deposit systems across the world [41]. It appears that this approach is, in general, naturally restrained to a small, regional scale. It can be imposed by law or freely organized by companies, and the study shows that the scheme can take many forms, according to economic, social, and cultural values of the area where it is implemented, following a general pattern as illustrated in Figure 2. As shown by Zhou et al., a successful operational mechanism of container-deposit policy can be backed by a more energetically expensive material-based recycling: when bottles are no more functional to be reused as such, or are accidentally discarded, their glass can still be recovered in a recycling plant to produce brand new bottles.

This flexibility is counterbalanced by the fact that every container type implies its own logistics and its own planning. This makes it simple and efficient where the system is already implemented, but where it is not, switching to it can appear as a burden since the whole production chain has to be re-considered.

The container-deposit model is still promising and is successfully applied in various areas for various products, but relies on both the involvement of consumers and the initiative of companies. Its main weakness is that it applies on small scales: a packaging product type has to be considered individually and the policy can only be applied at a local level, to avoid counter-productive logistic costs and emissions.

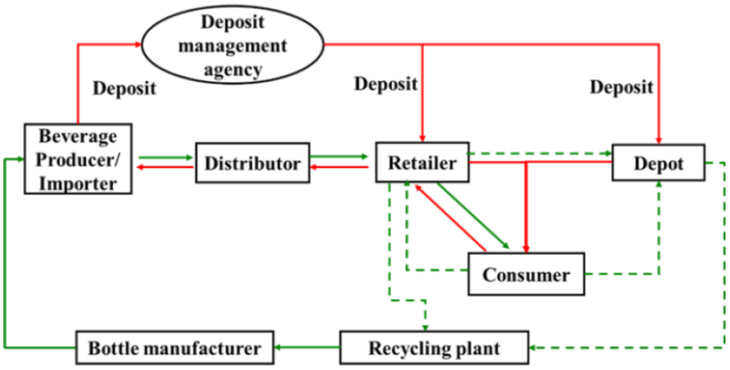

Figure 2. General diagram of the operation mechanism of the container-deposit logistics of beverage glass bottles by Zhou et al. [41]. The red arrows correspond to the deposit flow (product recycling), while the green arrows represent the alternative material recycling flow, in the case the bottles are discarded.

3.2.2. Ecover: Filling Up at the Shop

A new product from Ecover takes the container-deposit model a step further by avoiding the collection of empty containers at the shop as well as the transport of the collected containers to and from the supplier. Instead, a filling machine is placed at the shop, which fills in the product automatically into the used Ecover container that is returned by the client. This machine takes the product from larger containers, which do need to be transported back and from the supplier, but this takes considerably less handling. The interesting point of this model is that there is no exchange of deposit money, or rather this is implicit in the reduced price of the new product, and that the whole organization involves only the three essential parties: the client, the shop and the supplier. Neither government regulation or deposit-collection technology are needed [42].

3.2.3. Pieter Pot: Packaging-Free Groceries

The Pieter Pot concept is an alternative for the container-deposit model in which the live shop is also eliminated [13]. The client orders products online and the company that does the delivery also takes care of the return packaging. Pieter Pot washes the packaging and fills it with new products. Since the packaging is reused many times (at least 40 times), it is possible to design a more luxurious type of packaging, one which would not be cost-effective for single use. This way, it is possible to make packaging more ecological, more beautiful, and more functional at the same time. Additionally, here, the deposit is implicit, like with a single-use packaging: the value of the packaging that is returned is automatically compensated for in the price of the new delivery. Initiatives like that of Pieter Pot can be organized without any role for any other parties than the client and the suppliers that wish to get rid of single use packaging.

3.3. Discussions, Advantages, and Limits

Those three business cases are slightly different approaches to fight the impact of the extremely short life cycle of the packaging of daily life products. Bottles or jars are simple objects and the shortness of one of their functional lives makes it easier to conceive several cycles.

It has to be mentioned that a product-based circularity is also largely present at an informal, individual level: from old clothes exchange to the use of abandoned buildings as shelters, venues, or workshops, not forgetting the simple act of refilling a bottle with tap water or reusing a plastic bag, people have always been giving new uses to discarded objects. Anyway, circularity cannot only rely only on small-scale individual initiatives to have a significant impact. Since it has to do with social behavior, the only things that can be done are promoting it and designing accordingly, i.e., making resistant products that are easy to fix, and most importantly that remain safe for potential informal second lives.

The role of design in product-based circularity is crucial since it has to reshape the result of decades of a single-use approach. In the case of a more planned approach, as mentioned earlier through the examples, not only products, but whole business models have to be designed and, even though bulk groceries potentially concern anything that can be contained in a jar, those models are slow and difficult to apply, as they imply changes at many levels in the supply chain. It mainly involves consumers, whose behavior is usually slow to evolve, and companies which can have little interest in changing a working linear business model, since the circularity criteria are not always taken seriously yet.

As this paper aims to address strategies for circularity on a broad level, and in particular with the broadest possible definition of *waste*, it is also worth mentioning that an approach from the *product* is applicable to simple objects like packaging, but is indeed more difficult in the case of complex objects, that may require dismantling to have some of their parts re-injected into a circular scheme, if the design allows so [43]. It becomes unrealistic when it comes to big and specific units like a power plant or even a battery. Furthermore, between the beginning and the end of the life of a product which lasted several decades like a vehicle or a plant, the technologies involved in it may have evolved or completely changed.

From another perspective, in a scenario in which a massive involvement in a product-based circularity from the whole society is successfully adopted, the previously accumulated waste, along with broken products which functionality is lost will still escape the circular scheme.

To summarize, a great advantage of such an approach is that this is maybe the most effective way to re-inject a product into a new life cycle, with almost no energetic cost and environmental impact. It can work well for short-lived simple products like packaging, which represent a significant part of the produced waste, in mass and in value.

Nevertheless, this approach cannot be sufficient because, on one hand, it is not applicable to every kind of *waste*, and on the other hand, even if it was, it would not only require to specifically re-design the life cycle of every single product (or function), but also of each tool producing it, and also the plant itself. Most companies have no interest in doing so and, most importantly, no means nor skills to shift towards a product-based circular scheme. It has to be kept, promoted and developed where it remains relevant, but other approaches have to be found for a more general, less specific management of waste.

3.4. Applications in Civil Engineering

As discussed, complex *products* such as buildings do not fit the principle of simple re-introduction into new life cycles. Nonetheless, it is still possible to apply some concepts of product-based circularity to optimize their use.

3.4.1. New Profit for Unused Capacity in Highway Bridges

Product level circularity aims to design waste out of the system by enabling new life cycles of the product or product components. Waste here not only refers to the discarded product/product components that are no longer useful but also refers to the unused properties/capacity of the products.

Unlike other products, in the engineering and construction industry, the design life cycle of buildings, bridges, and other civil infrastructure is much longer, usually ranging from 50 years to 150 years. Due to the high perceived risk, they are designed and constructed in a very conservative manner. As a result, many of them are built much safer than the design requirements. For example, the Langesand bridge is found to have 30% reserve capacity concerning its critical limit state of deflection [44]. A highway flyover bridge in Singapore possesses at least an additional 30% loading capacity after twenty years of operation [45].

This additional capacity, which was achieved by consuming extra raw materials and energy when the bridge was built twenty years ago, is considered another kind of “waste” since it has never been used. To make use of it, Cao et al. introduce the additional loading capacity into the framework of operating profit optimization. The unused loading capacity enables a higher volume of vehicles and a higher proportion of heavy vehicles, thus further leading to the increase of toll profit. In the case study of a two-lane highway [45], at least 18% additional profit could be achieved.

3.4.2. Adaptable High-Rise Buildings

Buildings are demolished for many reasons including structural failure, being out of style, or to create space for new urban planning. When it comes to high-rise buildings, one of the main reasons is usually not structural deficiency but because they fail to respond to new demands. Once built, the high-rise building is less adaptable to change than low-rise buildings due to the technical difficulty in renovation and high cost.

One recent study focuses on the adaptability to the function change of high-rise buildings. In the design, a floor that is initially designed for residential use could serve other functions, e.g., gathering, office, healthcare, prison, industrial, lodging, education, sport, or shopping in the future [46]. Each building function has its specific requirement and considerations. The study identifies and investigates three dominant parameters, i.e., floor to floor height, reserve capacity (floor and foundation) and floor openness. By considering these three parameters, an adaptable high-rise building is designed. The building could quickly adapt to all the building functions with less than 50% extra materials. The Building Adaptability Indicator of the new design is three times the traditional design.

3.5. Mixing Approaches: Recovery of Materials from Metallurgical Anodes

As a way to introduce the material-based strategy and conclude on the product-based one, and most importantly to highlight their complementarity, it is interesting to mention an example of an hybrid approach.

A company, Magneto [47], produces electrodes for metallurgy. The anodes are made of titanium with an IrO_2/Ta_2O_5 coating and platinum contacts. Several years ago, customers sought to return their end-of-life anodes, and Magneto developed a process to reuse the core of the anode by removing the old contacts and coating, including remains of the metallurgical smelt, and replacing it with a fresh contact and coating. The old coating is removed, and then the surface of the anode is polished, by sandblasting with aluminum oxide. In this way, a mix of metals, including the Precious Metals (PM) iridium and platinum end up in the spent sand, at concentrations of the order of 0.1 mass% Ir. It is interesting to recover the precious metals from the spent sand to a concentration of about 1 mass% Ir, which would make it recyclable for the relatively small amounts of sand involved in anode recycling. Platinum-group metals and especially iridium have supply problems, and recycling can be a strategic advantage for users of these metals.

It has been made possible to concentrate the precious metals in the spent sands for further extraction and re-use as new coating material. On the other hand, the clean anode core can be re-coated using recovered PM to make a new electrode without having to reprocess the titanium, which would be energetically way more expensive. Here is illustrated a good combination of both approaches: recycling is here considered at the material level for the thin (and probably worn out) coating layers, while the core is directly re-used as such (thus at the product level) after sanding.

4. Material-Based Circularity

Any product which does not have its life cycle planned becomes *waste*. The functionality of an object may be lost but the material properties could remain valuable in many cases: recovering value from it is then much more relevant at a material level (see Figure 1, towards the right side of the graph).

A well-known example is the recycling of glass packaging, which is often separately collected to be melted again into new similar products [48]. A wide range of materials found in waste could actually follow a similar path, but some technological challenges have to be overcome.

4.1. Concept and Technological Challenges

Recycling, i.e., circularity based on the recovery of raw materials, is the most widely implemented activity for extending the functional lifetime of materials after maintenance and repair. Unlike maintenance and repair, however, recycling presents strongly different results whether expressed in terms of the *mass* or in terms of the *value* of the materials that are kept in the cycle. It is quite common for European countries to recycle up to 70% of the mass of their waste into new raw materials. It is extremely unusual, however, that more than 20% of the original material value in the waste is recycled. This difference is partly due to the fact that some easy-to-recycle bulk materials, such as steel or stone building materials, represent a large fraction of the mass of our waste but not a correspondingly large fraction of the value: the material value of concrete, steel, polyethylene, and copper per ton are EUR 35, EUR 400, EUR 1100, and EUR 5000–7000, respectively, differing by orders of magnitude. However, a deeper cause for the large difference in mass- versus value-based performance is that the recycling industry lacks advanced technologies for precise, high-speed characterization of materials in waste. Nor is it able to sort mixtures of particles automatically into a multitude of different materials at an acceptable cost. This lack of technology is a prime cause why the recycling industry cannot meet the demand for advanced and accurately defined materials that are at the basis of high added-value manufacturing and construction industries. In order to make the recycling industry operate at the same level as the primary materials industry, fast, high-precision characterization must be combined with high-speed particle manipulation for sorting, and recycling industries must adopt a digital representation of the material flow from input waste to raw material products.

4.1.1. Digital Recycling

Operating a largely sensor-based and robotic sorting process dealing with a multitude of different material specifications cannot be achieved without deep automation. Even the hand-sorting of packaging in Eastern European countries, where the material specification is conveniently linked to a brand, and a hierarchical organization of hand-pickers costing as little as EUR 3–4 per hour is instructed on the basis of detailed laboratory analyses about the selection criteria for each product class, is being replaced by NIR sorting. The present research aims at a complete mapping of waste flows in terms of a full material specification (Figure 3), so that completely automated sorting facilities are able to extract precisely defined materials (Figure 4) [49].

Figure 3. Near-Infrared (NIR) scanning of plastic flakes samples from waste to build databases. Each particular plastic formulation have a distinct fingerprint with its NIR spectral features which can allow, if carefully processed, for an extremely fine and specific sorting.

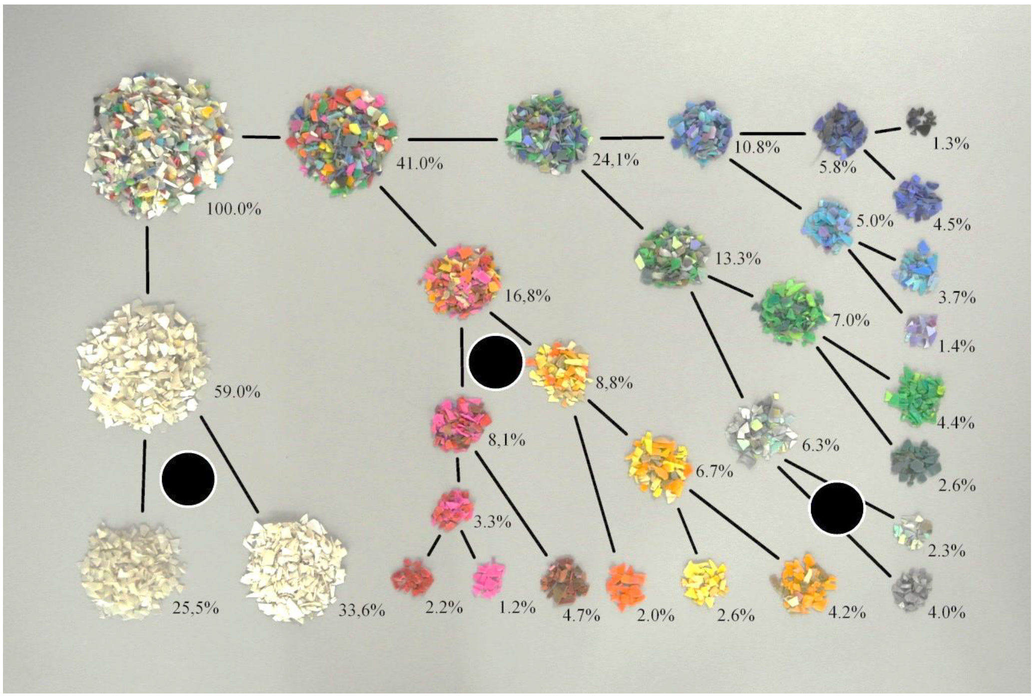

Figure 4. Illustration of successive steps of logarithmic sorting, considering only the color of plastic flakes [49].

4.1.2. On-Demand Recycling

Traditionally, recycling operations are focused on extracting a combination of broadly defined products from a waste flow, while minimizing the cost (often the amount) of residues. Such operations are responsible for finding an outlet for their products (and residues) and buyers may be geographically far from the waste sources. Digital, high-end recycling allows the use of recycled materials closer to the source of the waste, as it is able to directly replace primary raw material production. Digital recycling allows also *on-demand recycling*, in which the end-user of the material or the intermediary metallurgical industry precisely instructs the recycling facility about the products it wants to buy, or even rents and controls the recycling process to extract it from the waste. In this mode of operation, the recycling plant essentially becomes a market, which serves customers to pick and choose the ingredients from the waste that are needed for their own production or metallurgical process and compete with each other on price and priority of access. Looking at the first laboratory process set-ups that embody the concepts of digital and on-demand recycling, it is clear that much is based on existing technologies from other areas of industry, and that the particle size range in which such concepts will be made effective in the near future is still very limited by available technology.

4.2. Case Study: Rigid Plastic Packaging

For the vast majority of waste materials, the goal is to implement technologies that can identify and separate multiple and specific compositions or types. Once isolated, they are much easier to recycle, thus allowing, in the best case, to recover their original value. This is now studied for various types of waste, from construction material (i.e., concrete) to scrap metal from household waste. Rigid plastics from packaging is a good example to show the current strategies in material-based recycling, but similar methods are developed for other materials [50,51].

4.2.1. Data-Driven Sorting

Plastics are massively manufactured, relatively new in human history, and have a chemical stability that makes most of them extremely slow to degrade in a natural environment. For these reasons, they are often at the center of public attention when assessing sustainability and circularity. Among those materials, packaging plastics represent a crucial part: they represent about 40% of the European annual demand (see Figure 5) and have the shortest average lifespan (for some common food packaging products, it can be less than one day) [52].

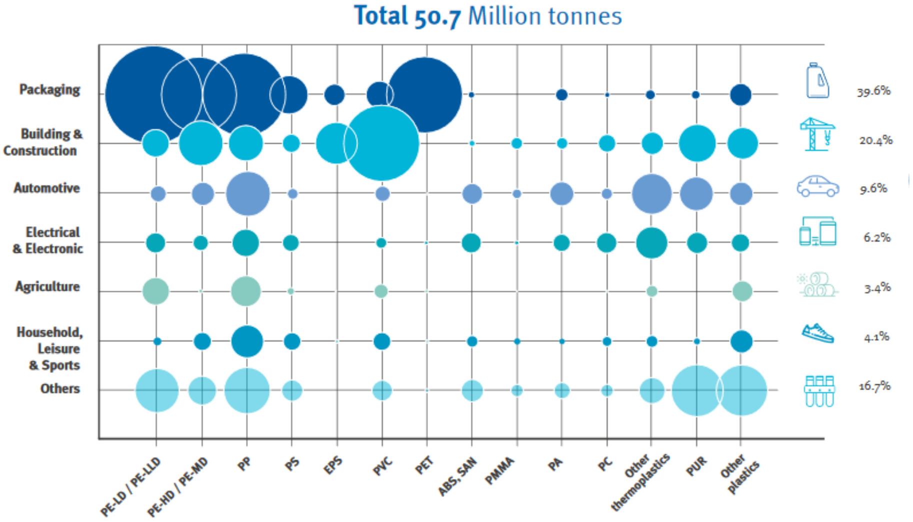

Figure 5. Distribution of plastic demand in Europe per polymer type and field of application in 2019. Courtesy of PlasticEurope [52].

Polymers offer extremely convenient flexibility: the possibilities of tuning cosmetic and functional properties with additives and/or by adjusting the production processes are nearly infinite, which make them adaptable to any specification, to match a particular product. For this reason, a resin type (e.g., PP) actually represents a wide array of materials. However, this creates, especially among packaging plastics, a huge variety in the waste flow, which is a major problem for recycling: it becomes impossible to control the composition and properties of a blend made using plastic waste as a raw material. The current most widespread approach consists of coarse mechanical recycling: melting back together what is effectively separated (the polymer classes which usually have enough differences in density between themselves) ignoring the different grades within a class of polymers. The result is a heterogeneous low-grade blend that can only be used in niche markets.

The loss in value of a unit of weight of the material and the potential saturation of niche markets makes this way of recycling not circular [53]. The aim would be to be able to design recycling processes that allow recovering the full value of the input materials.

One route is to use the "breaking down to the smallest unit" approach. It consists in trying to isolate all the chemical components back to their original state (monomers, additives…) to reformulate a plastic. More than just component separation, it implies the use of methods such as pyrolysis and solvolysis to achieve the depolymerization of the chains [54]. This is known as "chemical recycling" and has only found really specific applications, the complexity of the method itself prevents it from being cost- and energy-efficient to be applied significantly [55,56].

Another approach is to consider that each particular formulation found in plastic waste has to be re-used in its original application, minimizing degradation and using only low-cost and environmentally clean processes. The definition of "application" is more or less precise, depending on how particular is the corresponding structure and composition of a given plastic grade. In this case, mechanical recycling, which is generally simple and energy-efficient, can be reasonably used without fearing much loss in properties, thus in value [57]. This way of recycling is not much different than the plastic objects are manufactured from plastic pellets by converters, just replacing pellets with secondhand polymer flakes.

The most important part is then the purity of the input: if incompatible plastics are melted together, the degradation of properties will occur [58]. Sorting is thus the process that has to be improved. More than separating the resin types, the challenge is to be able to recognize plastic flakes according to what defines their particular applications: their aspect and functional properties [59].

In order to apply a material-based recycling scheme, sorting facilities have to be designed to deal with a large number of polymer formulations with flexible definitions. Here adaptability is the key and the point where nature comes as an inspiration in broad terms: a new structure, object, or being is created using only the relevant available resources, depending on what is needed. To fit a truly circular scheme, sorting has to be, on one hand, adaptive and flexible to be demand-oriented and able to deal with different and evolving formulations, and in the other hand extremely precise to make the following step, mechanical recycling, harmless for the quality of a given recyclate. In other terms, the sorting method must be able to be applied to any plastic definition with minimal error.

4.2.2. Deep Sensor Sorting of Rigid Plastics

It is first necessary to find an easily measurable property (or set of properties) that would define every possible *type* that can be defined by potential customers. As density sorting is widely used to separate between resin types, near and mid-infrared spectroscopy (along with color characterization) seems to be the best candidate for deep sorting [60]. Specifications about secondhand plastic flakes could take the form of ranges of properties, particularly mechanical (functional), rheological (processing-related), and visual (aspect) properties. If the latter is perfectly captured by color cameras, the other two, being related to crystallinity, molar masses, and additives, may all be expressed in infrared spectra [61–63].

However, the link between spectra and properties is too complex to establish simple correlations. Moreover, the diversity of functions among plastics could make customers' specifications take various forms. The challenge is to be flexible. This implies a relatively new way of using sensors: instead of acquiring simple data that are directly processed, a huge representative database has to come first to picture the diversity of plastics found in waste, with on one hand infrared spectra (and color data) and, on the other hand, commonly considered properties such as tensile strength, melt flow rate, Young's modulus, and so on. Such a database can be imagined as a multidimensional cloud, whose dimensions are all the wavelengths of an infrared spectrum, plus the color data (red, green, and blue for RGB for instance). A point (or small cluster) would represent the fingerprint of a given plastic flake. This way, clusters and ellipsoids may appear at different scales, representing different possible definitions of a plastic formulation.

This concept draws the scheme of what can be called data-driven sorting: a database that represents the characteristics of all plastics found in waste would allow defining a target, translating it to a range of spectral shapes and/or colors, and finally, with appropriate sensors and separating device, it would become possible to separate any plastic or specific group from the waste flow. Another crucial point is that with such a database, if representative enough, the relative importance of a certain formulation/group of plastic in the waste flow can be known by considering the number of data points sharing similar characteristics within the boundaries of a definition. This importance can be calculated in weight, if the database provides densities and dimensions of plastic flakes or objects.

This novel route would eventually lead, for instance, to the possibility for a shampoo bottle manufacturer to use secondhand plastic flakes from his own shampoo bottles to make new ones, instead of using only raw materials. Logarithmic sorting [49], understood as a way to sort clean flakes from rigid packaging waste into a large number of different plastic grades using simple successive sorting operations (dividing the flow into two roughly equal parts according to a rule that can be changed at every step, as pictured in Figure 4), could complete this approach. A big database, as described above, would allow to define successive groups, or ways to divide the flow, in an efficient way. The number of successive steps will obviously determine the organization within a plant and the cost of a given plastic grade.

The combination of these concepts could lead to a significant step towards a circular economy of rigid plastics. Deep sensor identification and logarithmic sorting rely on existing technologies, and secondhand flakes could be used as raw materials without changing the existing processes of plastic converters, provided that the purity of those flakes is excellent. As in the biosphere, when tissues and materials degrade to molecular levels after a functional period of time, they become available to be consumed and used again, and the smallest loops have the lowest impact on everything else. This last feature is of little relevance for the perfect circular balance of nature, but it becomes crucial to reduce this impact when it comes to human activities of production.

The creation of a circular economy of rigid plastics will also have to deal with mid-term issues, such as the recycling of plastics that contain toxic substances, which can be discovered and banned by laws, breaking a loop [64]. The act of recycling them could increase their problematic aspects, and an extremely good monitoring of chemicals has to be implemented. These issues are anyway common to any material-based recycling strategy.

In a broader context, data-driven strategies are today the most likely to be implemented at large scales: knowing the composition of a waste flow is the best way to determine where there are more or less valuable parts, whether it is more or less difficult (thus more or less expensive) to extract a defined part. To make it possible, necessary conditions are:

- Separate first, as much as possible, the waste flows that have to be considered separately (i.e., hard plastics, metal scrap . . .). This can partly be done by the consumer, using different bins for different waste types, depending on the local waste-collecting policies, and can also often be done again at the level of a recycling plant with physical methods.
- In a given area (a country or region, typically), representative data of the concentrations and properties of each material present in a given flow must be acquired, through sampling and analyzing elements from the flow. In the case of hard plastics, near-infrared spectra and color data have been proven to be suitable technologies to identify any formulation [49]. It is now up to scientists to build local databases, compare them and monitor their evolution in space and time, and ultimately know precisely what can be found in waste and to which extent.

Once waste is adequately characterized and the relatively cheap technologies are implemented (i.e., automatic sorters developed and recycling plants designed), it should be a matter of time until the new recycling methods are widespread. If the quality of recyclates is good enough (and it mainly relies on sorting), recycling plants will be equivalent to raw materials producers, but with simpler processes and energy-efficient technologies, relying on a resource with almost no value: waste. This will hopefully make recycled materials cheaper than their raw equivalents, quickly shifting the economy of materials towards a much more circular scheme.

5. General Discussions and Conclusions

A circular economy of materials is a goal towards which humanity has to aim. The diversity of examples above, from plastic packaging to construction materials from buildings, and from material as such to entire products (i.e., glass containers), plenty of directions are still to explore to achieve better recycling. By "better recycling" we mean of course *more circular*, and it is important to define first what is meant by circularity. What is proposed here is to consider the material flow, through life cycles, and to evaluate the loss in value it undergoes at each cycle [53]. An ideal case would be no loss in value, by recycling the products, parts, or materials into the same, or similar objects (in terms of functionality, thus also in terms of value). This would also allow to drastically reduce the part of the waste flow that has to be discarded through potentially problematic processes like incineration or landfill.

In order to facilitate a shift towards circularity, a first necessity is to introduce, by the means of scientific consensus and public policies, a robust definition of circularity, associating it with indicators (for instance, if assessing a life cycle, the percentage of original value recovered, taking economic, energetic and ecological costs of re-injection into a new cycle into consideration). From such guidelines, standardized evaluation methods can emerge for any recycling process. This also means that even the very concept of circularity will be publicly more robust and clearer in meaning, preventing it from being abusively used for marketing purposes in counterproductive ways (regulation of greenwashing [65]).

In parallel, it has been shown above that diverse strategies to recycle can be carried out at different levels. It is important to identify them, their possibilities, and at which level of the economy of material they can be located. In order to efficiently go towards *more* circularity, isolated initiatives are no more relevant, but every actor in the global material flow has to cooperate with its customers, its suppliers, and society as a whole to achieve the most circular scheme possible.

In this paper, a classification of different recycling strategies has been proposed, as a spectrum between two extremes: recycling *materials* on one hand, and recycling *products* on the other. The former would look like mining into waste: identifying the desired materials into a flow, extracting and then recycling them. A product-oriented approach would rather avoid destruction of particular objects through discarding, and organize closer loops in which products do not have to be re-manufactured.

If those approaches are complementary, they are not efficient at the same scales: a product-based approach is relatively easy to promote at an individual scale with the concept of re-use, and up to companies that can organize the life cycle of some of their products. It is clearly the most material-efficient approach, as some products or parts can go through several life cycles without losing value at all, and the processes involved in recycling such products are often relatively simple, cheap, and clean (re-coating of electrodes, washing and re-conditioning glass bottles…). However, by scaling it up, the diversity and complexity of manufactured products and particularities would need heavy planning policies which are not likely to be easily implemented, if possible at all. The complexity of some products makes them simply impossible to even dismantle into functional parts, but still, they do not have to be considered out of the material flow.

Dismantling can represent an intermediate approach for complex products such as cars: parts can be re-used and this process is often carried out spontaneously by individuals or companies, whenever it is economically interesting and easy to do. This process can be encouraged by an efficient product design, for instance by making different parts easily separable and using as few different materials as possible. However, again, it concerns individual and specific products, and little more than promoting it can be done at public and scientific levels.

Currently, the focus has to go on a more general, all-encompassing approach: considering the waste flow like a mix of primary resources, and extracting materials in it, just like the cycles undergone by materials and substances in the biosphere, that are continuously transformed into something *useful* to a living organism. This approach has two main challenges: extracting and recycling/re-processing. For the latter, many efficient methods already exist but are limited by the purity of extracted materials: technologies and policies have to converge at this point to have the strongest impact on circularity. Sorting strategies have to be developed and promoted at the public level, along with new business and logistical models. The example of glass recycling in many countries is a success that may encourage the same for other materials: rigid plastics, scrap metal, concrete…

As identification and sorting technologies become available and well known in scientific research, they have to aim for implementation at an industrial scale, and will soon multiply when it shows its economic and ecological efficiency. Those processes have to remain as accessible as possible as the aim is to impact circularity at a global level, but their reliability and precision remain the crucial point for efficient recycling. The goal is to re-inject as many high-quality materials into new life cycles with no value loss. This would even act as a rescue net for products escaping more efficient but smaller-scaled and less systematic product-oriented strategies.

A new vocabulary and new business models would emerge, such as recycling plants acting as materials markets. Ultimately, as waste will become more valuable, much more effort will be put on avoiding waste pollution.

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Abbreviations

The following abbreviations are used in this manuscript:

IE	Industrial Ecology
EoL	End of Life
CE	Circular Economy
SD	Sustainable Development
EASAC	European Academies Science Advisory Council
OECD	Organisation for Economic Co-operation and Development
PP	Polypropylene

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