sustainability

MDPI

Article

Challenges to the Circular Economy: Recovering Wastes from Simple versus Complex Products

Carly Jacobs, Katie Soulliere, Susan Sawyer-Beaulieu, Abir Sabzwari and Edwin Tam *

Department of Civil and Environmental Engineering, University of Windsor, Windsor, ON N9B 3P4, Canada; jacob11p@uwindsor.ca (C.J.); soulliv@uwindsor.ca (K.S.); susansb@uwindsor.ca (S.S.-B.); sabzwa11@uwindsor.ca (A.S.)

* Correspondence: edwintam@uwindsor.ca

Abstract: The circular economy re-interprets the recovery of materials by promoting designing out waste from products, retaining materials for reuse, and emphasizing key elements universally accepted for sustainability. The current efforts to target, isolate, and reduce single-use items, particularly plastics, have only recently begun in earnest. Unfortunately, the recovery and recycling of materials have been disrupted by global market uncertainty, and recently, the COVID-19 pandemic. While the pandemic and its impacts complicate materials recovery, the core of the circular economy still depends on efficiently capturing and returning spent materials for production. Arguably, our perception and common understanding of the recovery process is influenced significantly by the recycling of simple consumer products, such as plastic bags and beverage bottles. However, there are greater difficulties when managing multiple materials from significantly more complex consumer products, for example, from end-of-life vehicles. This paper presents an overview of how waste recovery-related issues vary between simple versus complex consumer products. Using food packaging, tires, cell phones, furniture, and end-of-life vehicles as examples, this paper provides a commentary on the challenges facing complex product recovery compared to simple consumer products in the Canadian context in order to establish how this classification concept can be beneficial for describing a given product and its materials recovery prospects. A categorization framework is developed and applied to these case study products to provide a relative comparison of product complexity.

Keywords: circular economy; material recovery; recycling; simple goods; complex goods; durable goods; repair; refurbish

Citation: Jacobs, C.; Soulliere, K.; Sawyer-Beaulieu, S.; Sabzwari, A.; Tam, E. Challenges to the Circular Economy: Recovering Wastes from Simple versus Complex Products. *Sustainability* **2022**, *14*, 2576. https://doi.org/10.3390/su14052576

Academic Editor: Nicholas Chileshe

Received: 23 December 2021
Accepted: 1 February 2022
Published: 23 February 2022

1. Introduction

Sustainability is one of the most commonly used yet least well-defined terms regarding the environment. Sustainability can refer to a variety of topics, from natural resource availability and populations to agriculture and energy: all have standards for sustainability that can vary based on cultural and environmental factors, making it difficult to settle on a conclusive definition [1]. Regardless of the exact definition, sustainability generally paints a picture of an ideal future that embraces nature; however, the term itself does not refer to any particular process for achieving that future and, because of that, is frequently difficult to operationalize on a consistent basis.

The circular economy initiative provides a potential path to a sustainable future by re-interpreting materials recovery and return from waste or end-of-life products and materials. It includes designing out waste and pollution, retaining products and materials for use to the greatest extent possible, and regenerating natural, ecological systems [2]. More importantly, the circular economy advocates a significant break from our current linear economy model and conventional business practices. Between 1970 and 2010, the annual global use of materials almost tripled to reach 75.6 billion tonnes, which could increase to 180 billion tonnes by 2050 if existing trends continue [3]. Arguably, the decades old paradigm of reduce, reuse, and recycle has never been more relevant. The circular economy's focus on the corresponding cursive paths of product, component, or material movement builds on this adage by introducing maintenance, reuse/redistribute, refurbish/remanufacture, and then recycling as a general hierarchy of technical material loops based on environmental and economic value and efficiency [4].

Unfortunately, current materials recovery systems and initiatives are not extensive or efficient enough to fully support a shift towards a circular economy. In Canada, overall rates of solid waste diversion remain well below 50% [5] despite widespread recycling and education programs. In order to facilitate the circular economy, used materials need to be captured and returned for production both efficiently and economically. However, the average person's casual understanding of recycling is influenced significantly by the recycling of simple consumer products, such as plastic food packaging, beverage bottles, and cardboard. Recycling is a common means of materials recovery for many such products, but the current struggles that a number of recycling programs in North America are facing underscore the significant challenges underlying recycling.

Conventional recycling practices have also recently been disrupted by global market forces. Since early 2018, China has restricted the import of certain wastes, including waste plastics, unsorted scrap papers, discarded textile materials, vanadium slags, scrap metals, scrap ships, compressed pieces of scrap automobiles, waste plastics from industrial sources, and wood waste and scrap [6].

However, the challenges faced are not only because of the loss of the Chinese market [6,7], but also significant methodological, technical, and societal issues that need to be addressed. Materials recycling facilities (MRFs) have faced multiple operational challenges, including:

- Identifying which materials are recyclable;
- Separating materials from one another;
- Ensuring purity and avoiding contamination that could degrade the value of recovered materials;
- Establishing or transporting to markets that could purchase recovered materials.

Such challenges tend to increase as products become more intricate or durable in design and production; contain multiple materials, particularly if some are hazardous; or consist of components that are intimately joined together. In terms of the potential for circularity, there are differences between simple materials and products compared to more challenging complex products [8]. Recycling is often casually thought of in terms of curbside recycling, which targets simpler products with minimal material variation or joint complexity. However, complex goods have potentially different characteristics that can impede recycling: there are practical limits to what can be effectively recaptured, returned, and reused, as shown by Reuter et al. [9] in their analysis of a modular smartphone. Furthermore, products from companies such as Niaga (carpeting) and Recover (textiles) featured as circular economy success examples largely involve recovering simpler products, or isolated or select materials. As a result, applications of circular economy strategies to multi-material, multi-component items remain challenging. The first objective of this study is to present an overview of the material challenges facing a variety of products in the Canadian context. The second objective is to establish how the classification concept of simple and complex products can be extended towards describing a given product and its material recovery prospects and challenges. Moreover, this description can form the basis for product redesign recommendations.

2. Methods—Simple versus Complex Products

There are significant issues surrounding the recovery of even the most commonly recycled products, such as food packaging and cardboard. These types of items are referred to as non-durable goods [10]. There are greater difficulties when managing multiple materials from what we identify as complex consumer products, including some of our largest and most complex consumer goods, such as electronics and vehicles. Durable goods [10] would also fall under this categorization of complex goods. However, we argue that the challenges from recovering such items are better expressed via their multiple aspects of complexity instead of the specific notion of durability [11]. The Ellen MacArthur Foundation [4] has proposed that "complex medium-lived" products are particularly suitable for circularity, but does not provide an in-depth definition or measurement of complexity.

As the push for a circular economy gains momentum, it is critical that the recovery potential of an end-of-life item can be accurately described. There is a unique opportunity for complex products in a circular economy because they often contain valuable materials or components that would be well suited for recovery through systems of reuse, refurbishment, or remanufacturing. However, this depends upon a product's ability to be separated into those components that can then be reused, refurbished, recycled, or otherwise managed appropriately.

There are many metrics and guidelines that exist to analyze recyclability, ease of disassembly, or sustainability for a wide range of products and circumstances. These can be ad hoc within the company or industry sector. Some are tailored to a particular type of item, such as construction materials [12]. Additionally, the scope of these metrics can vary greatly, from specific operations such as calculating the time required to disassemble an item [13], to assessing the overall circularity of a product [14,15]. Methods for assessing product recovery that specifically discuss product complexity, include those described by Roithner et al. [16], who use statistical entropy to measure the complexity of a product and its subsequent recyclability, and Sultan et al. [17], who developed an approach for identifying which products should be recycled using material security, recycling technological readiness level, and product complexity based on the ease of material separation. Furthermore, the use of product characteristics has been investigated before to improve design-for-recovery efforts [18,19], and they could potentially be further refined as design criteria. Almoslehy and Alkatani [20] note that the design process has a significant impact on the maintainability and recyclability of complex products. However, it is the feedback from the realities of recovery efforts flowing back to designers that is currently lacking.

We propose the following in Table 1, modified from Tam et al. [21], as a potential approach to characterize the possible differences in recovery potential between products in order to categorize them as either "simple" or "complex" based on common design features, recognizing that there is a continuum of product characterizations within them and that there will be some exceptions and unique circumstances. Much of the prior-referenced literature provide methods for evaluating recovery for specific products but at a minimum require detailed product level information. Instead, this approach broadly assesses major issues impacting recovery to provide an initial but structured screen of the challenges that might be encountered for recovery and eventual redesign. This is especially helpful if there is no immediate access to detailed product-level information.

Table 1. Potential Characteristics of Simple vs. Complex Consumer products.

Characteristic	Simple Consumer Product	Complex Consumer Product
Material Variability (MV)	Usually, single material in any one product, but with many possible variations of any one product.	Usually, several materials in a single product
Material Integration (MI)	None usually. Products are distinct from one another, or weakly connected.	Different materials are joined together using adhesive, welding, fasteners, etc.
Material Complexity (MC)	More basic materials (paper, common types of plastic, glass, etc.)	Materials intended for longer-term use, and possibly in difficult or harsh environments.
Product Form Factor (PF)	Smaller, lightweight, compact or semi-compact in identifiable geometric shapes (boxes, drink containers, flat packaging).	Highly variable, ranging from small to large. Small items might be dense despite compactness. Range from simple geometric shapes to unusual configurations molded to fit specific needs.
Recovery Initiatives (RI)	Often community- and convenience-based (e.g., Blue Box bins, deposit centres).	May include repair, refurbishment, or reuse potential. Usually, dedicated facilities or specialized pickup or drop-off services for reuse or disposal.

Five products at various points on the spectrum of simple to complex consumer products, namely plastic food packaging, tires, mobile phones, furniture, and end-of life vehicles, have been selected for examination due to their everyday use and wide range of characteristics. This paper provides a brief state of the current recovery landscape in the Canadian context and commentary on some of the distinct challenges facing each product, followed by a discussion of how these challenges relate to the classification concept of simple vs. complex products and the specific characteristics outlined in Table 1. We emphasize that the proposed characterization is not definitive, but rather an illustrative approach to understanding recovery challenges.

3. Existing Recovery Methods and Challenges Facing Effective Recovery

3.1. Plastic Food Packaging

3.1.1. Recovery

Plastic food packaging is one of the most common and abundant examples of a simple consumer product. In 2016, 47% of the 3.268 million tonnes of plastic waste discarded in Canada was some form of plastic packaging [22]. Canada has committed to reduce plastic waste though international agreements, such as their adoption of the Ocean Plastics Charter in 2018, which includes pledges for "significantly reducing the unnecessary use of single-use plastics" and to "foster awareness and education efforts on preventing and reducing plastic waste generation" [23], as well as domestic initiatives like the Strategy on Zero Plastic Waste. However, current efforts to reduce material-use, such as single-use plastics, have only recently begun [24]. The recently proposed ban from the Canadian government targets six types of plastic items, including plastic checkout bags and some types of take-out food containers [25]. Programs to replace single-use plastic food packaging with reusable alternatives in Canada, such as the Reusable Container Program at Bulk Barn, are not commonplace, and mechanical recycling remains the major means of diverting plastic food packaging from the disposal waste stream [22]. Additionally, there remain liability concerns if the item is reused in critical applications where there are safety or contamination concerns.

In Canada, household waste collection and recycling vary by province and municipality, but "Blue Box" curbside collection programs are common for recycling paper, plastics, cans, and glass. For example, in Ontario, municipalities with a population of over 5000 people are required by law to have a Blue Box program that collects five basic categories of items, including PET plastic food and beverage bottles, and at least two additional supplementary categories, which can include, among other non-plastic options, expanded polystyrene food or beverage containers, low-density polyethylene used in grocery and other types of bags, and rigid plastic containers [26]. Recycling is one of the most common metrics of environmental "success", but there are many challenges. In Ontario, for example, the current government has announced a major overhaul of its curbside recycling efforts because of low success rates (about 40%) despite decades of promotion and collection and the relatively straight-forward messaging behind programs such as the Blue Box. Ontario is updating their Blue Box curbside program to shift recycling responsibility to producers [27].

3.1.2. Challenges to Recovery

There are multiple challenges that currently limit the effective recycling of plastic food packaging, including low collection rates. Only 23% of plastic packaging in Canada is diverted and sent to a sorting facility, with 15% successfully reprocessed [22]. Although this seems low, it represents a large portion of the plastic waste that is actually recycled in Canada: 88% of all recycled plastic resin comes from plastic packaging [22].

A lack of standardization regarding which materials are accepted for recycling contributes to low diversion rates because each municipality has different requirements for plastic recycling, and many do not accept food packaging that contains lower-grade plastic. In 2016, Ontario introduced the Resource Recovery and Circular Economy Act and the Waste Diversion Transition Act, which enables further legislation to address waste management issues in the province. Key changes include a shift towards producer responsibility for waste materials, with producers adopting more financial and legal responsibility for the waste they produce [28].

Cost is another constraint to recycling plastic food packaging, with 95% of the material value of plastic packaging lost after its first use [29]. Ranging from a cost of CAD 723 per tonne to recycle HDPE, to CAD 2255 per tonne for polystyrene, plastics are much more expensive to recycle than other blue bin materials in Ontario based on 2012 data [30]. Items such as newsprint cost CAD 85 per tonne to recycle, and aluminum cans actually have a net gain of CAD 286 per tonne [30]. High contamination rates have further led to overall increasing costs of blue bin recycling programs. Contamination, which includes non-recyclable materials and food residue, results in increased labour costs for collecting, sorting, and disposal. Contamination rates can be as high as 25% in cities like Toronto [31]. Nevertheless, from a comprehensive perspective, low revenue generation, high recycling costs, and contaminated materials all contribute to the high costs of recycling plastic food packaging.

Mixed-material waste streams are typically reprocessed through secondary recycling processes, which for plastics can reduce the mechanical properties of the material: these can really only be processed into lower value end products [32]. Various types of contaminants including chemical additives, inorganic elements, and flavour and aroma compounds from food contents are also common in recycled plastic from food packaging [33]. This reduced quality after recycling limits the potential of the material to successfully flow through the circular economy [4]. For example, only 7% of PET plastic bottles are recycled back into bottles, while 80% become polyester fibres for items like clothing or carpet [29]. There are currently fewer recycling opportunities for these products, resulting in open material loops where large amounts of materials are lost from the circular economy.

Perhaps the greatest challenge to recovering simple plastic food packages are the diversity of products to meet consumer demands, and their diverse range of materials and plastics. Twenty-three material types, both plastic and non-plastic, are acceptable in Ontario's Blue Box program [30]. In recent years, the different types of plastic containers used for food and beverage packaging have increased, shifting blue bin contents from a mix of mainly paper, metal cans, and plastic bottles, to now include a wide variety of plastic food and beverage containers of all sizes and materials, causing a problem known as "the evolving ton" [31]. Between 2003 and 2013, the percentage of "non-core" Blue Box materials, like aseptic containers and plastic film, which are characterized by both low recyclability and revenue, increased from 7% to 11% [34]. These materials complicate sorting and recycling, while significantly increasing costs without significantly increasing overall diversion rates [34]. The diversity of plastic food packaging poses difficulties for both recycling facilities, as they must find new ways to sort and process these materials, and consumers, who struggle to keep up with changes to packaging types and recycling regulations.

Changing the design or material contents of a product to reduce the weight, known as "lightweighting", has dramatically reduced the amounts of materials used in individual plastic packaging units. For example, since 1970, the weight of a 2-litre plastic soda bottle has decreased 31% [35]. Although this technique supports the core principles of the circular economy by designing out waste, it does introduce potential challenges to recycling because smaller and lighter containers can be more difficult to sort and process [31]. This may be especially challenging in sorting facilities that use automated machinery that depend on identifiable characteristics to sort items.

3.2. Tires

3.2.1. Recovery

The recovery of end-of-life tires (ELTs) is one of Canada's most successful waste diversion programs in terms of diversion rate. Tire management programs are run by stewardship organizations at the provincial level (and in the territory of Yukon). In Ontario, ELTs can be taken by consumers to collection sites, which may be municipal collection sites or those located at private businesses, such as auto repair facilities or car dealerships. In 2019, 376,915 tonnes of ELT were collected in Canada, with a 10-year average diversion rate of 98% [36]. In a study of 20 global ELT management systems [37] Canada had the highest percentage of ELTs going towards material recovery, which is of higher priority to the circular economy than the energy recovery of tires, which is common in some regions. Recovered ELTs in Canada have many uses, such as providing crumb rubber, molded rubber, and tire-derived aggregate [36]. Tires can be remanufactured to extend their lifespan through the process of retreading, which accounts for 44% of commercial tires in the USA and Canada [38].

3.2.2. Challenges to Recovery

Tires are made of three main materials: steel, rubber, and textiles. Because tires typically contain multiple different rubber compounds, the process of separation and devulcanization is difficult and underdeveloped. As a result, the ELT rubber is reduced in size and recycled in its composite form [39]. The most challenging materials to recycle from tires are textiles, due to contamination and low value; they can also become a hazard in recycling operations as dust and fibres build up on machinery [39].

Despite the success of tire recovery, some challenges remain. For example, the closed-loop recycling of rubber into new tires is rare due to quality and performance factors and the previously mentioned difficulty of separation and devulcanization [39]. As a result, rubber from end-of-life tires is commonly recycled in open-loop or downcycling applications, such as synthetic turf or molded rubber products [40].

Additionally, the amount of tire retreading has decreased significantly in the last 20 years due to an increase in low-cost imported tires. These ultra low-cost tires see only about a third as many retreads manufactured for every tire sold when compared to the sale of premium tires [38].

3.3. Mobile Phones

3.3.1. Recovery

In 2019, 53.6 million tonnes of e-waste was generated globally, of which about 9% is classified as "Small IT and Telecommunications Equipment", such as smartphones [41]. Canadians generate 20.2 kg of e-waste per capita, much higher than the global average of 7.3 kg [41]. Approximately 34.4 million Canadians (91% of the population) have a mobile phone subscription, up 1.2 million from the previous year [42]. In Ontario, the management of waste electrical and electronics equipment (WEEE) transitioned to a new program enforced by the Resource Productivity and Recovery Authority (RPRA) on 1 January 2021.

3.3.2. Challenges to Recovery

In a study of the recovery of cell phones in Canada, some challenges that were identified include lack of awareness about recycling, lack of efficiency of reverse logistics, cost, and lack of incentive for consumers [43]. Low collection rates are a significant barrier to increasing the recovery of mobile phones, as less than 14% of Canadian e-waste is documented as properly recycled [41]. The most recent Statistics Canada information shows that 17% of Canadian households had unwanted cell phones to dispose of in the last year [44]. Although 64% of respondents reported the reuse or recovery of the devices through methods such as taking them to a drop-off centre or donating them, 3% report putting them in the garbage, and 40% still had the cell phones at the time of interview [44]. This tendency of consumers to keep unwanted cell phones and other electronics is often due to confusion about how the items should be disposed of and data security concerns about the information on their devices [45].

E-waste contains many different components and materials, some of which can be hazardous materials that require caution when dismantling and recycling. Most phones available on the market today are not designed for dismantling or repair by consumers, and have limited options even from professional services.

Although some e-waste recycling can be expensive, the value of the materials embedded in electronics is substantial. It is estimated that the 435 kt of wasted mobile phones around the globe in 2016 contain raw materials worth EUR 9.4 billion [46]. There is 100 times more gold in a tonne of smartphones than in a tonne of gold ore [45], which can make recycling an increasingly attractive and profitable venture as primary resource extraction becomes more difficult and expensive. One potential way to incentivize the recovery of the most valuable raw materials contained in e-waste is to include recycling indicators based on monetary value recovered rather than by mass, which could encourage the recovery of high value materials that are present in small quantities [46]. Even more value can be retained from waste mobile phones if they are able to be reused or refurbished, as the average selling price of a used smart phone is many times higher than the value of the raw materials it contains [46]. However, the increasing prevalence of electronic goods and the often-limited lifespan of smartphones, due to short replacement cycles caused by technological updates or the perception that an item is outdated [46], makes proper recovery of this waste stream difficult.

3.4. Vehicles

3.4.1. Recovery

Due to the high value of vehicles, both whole vehicles and vehicle parts have a relatively high level of reuse in Canada. In 2017, used vehicles made up 33% of retail vehicle sales by value [47]. For reused parts, the North American dismantling and recycling infrastructure for automobiles is more market driven than in other jurisdictions. Nevertheless, there are still valuable lessons from observing how recycling and recovery operations function. North American ELV-dismantling facilities are nominally divided into two major categories: (1) full-service and (2) self-serve ("U pull it") facilities. Some facilities feature both, but the distinction between the two is useful. For full-service facilities, resalable parts are removed from the automobile, inventoried, and stored either outside or inside in the facility. They may also be stored "on board" the vehicle itself, and then the parts can be removed when there is a demand for them. For self-service facilities, customers recover the parts themselves at a reduced price. In either case, it was observed that the availability of a component that can be returned as a part for reuse versus a component destined for materials recycling depends on several infrastructural and operational parameters. In particular, the amount of land available for storing the ELVs is critical: less available space means a particular hulk can stay on site for only so long before it is deemed not valuable, and has to be cleared out to make room for ELVs with parts that are likely to have more resale value. Presumably, this may affect self-service operations more because the entire vehicle has to be stored, whereas in full-service facilities, valuable parts are more likely to be already removed and stored as efficiently as possible. In North America, vehicle ownership averages about 12 years [48]. The reuse of vehicle parts depends on having a sufficient inventory of relevant parts to supply the demand for older car parts. While this is only one example, it illustrates that the recovery approach and specifics of simple consumer products may not apply equally well to complex products. Instead, recovery operations that have flexible and extended parts storage that permit greater potential for their resale and reuse are more likely to be greater contributors to the circular economy than relying on recycling alone.

Because of the global nature of the automotive manufacturing sector, many original equipment manufacturers (OEMs) operate to international specifications, including meeting EU regulations on vehicle recyclability: each vehicle sold that is destined for the EU market should currently have 95% recyclable content in 2019 [49,50]. While this is commendable from a policy viewpoint, there are significant challenges to the actual success of recycling. For example, within a 10-year span in Canada, 15.3 million light-duty passenger cars and trucks have been retired [51,52]. Based on an average weight of 1.364 tonnes per of end-of-life vehicle (ELV), excluding fluids and tires [53], these 21 million tonnes of ELVs were shredded. This shredding produced an estimated 16.8 million tonnes of metals (approximately 80% by weight of the ELVs) that were recycled, and 4.2 million tonnes of ELV-derived shredder residue (i.e., 20% by weight of the shredded ELVs) [53]. This shredder residue was mostly landfilled, occupying approximately 7.5 million m^3 of landfill space based on a shredder residue mean moisture content of 6% wt. moisture [54] and a compacted solid waste specific weight of 593.3 kg/m^3 in landfill [55]. In 2016, the automotive sector generated 9% of the total plastic waste that was discarded in Canada [22]. The claim of recyclability for any product can therefore be far removed from the actual recycled amounts. Even in the case of automotive recycling above, where a large portion of metals are recycled, the sheer scale and volume of disposed automotive waste means a significant, absolute amount of material (primarily the non-metal fraction, including plastics) is not recovered and is landfilled. Examples of recycling successes may be anecdotal or are industry-specific situations scenarios; while these are commendable, they would not qualify as global successes.

3.4.2. Challenges to Recovery

In complex products, materials need to be liberated from one another to achieve greater purity. In contrast, simple products such as bottles and cardboard may be mixed together in a recycling bin but are not physically connected to one another. Other disciplines, such as product manufacturing, have developed metrics or approaches related to the disassembly of products, or the reverse assembly of components to ideally remove them for direct reuse in remanufacturing. These are potentially useful techniques to inform design from the outset, but they appear data and operationally intensive (e.g., [13,56,57]), and the examples used for discussion typically involve smaller, compact items (e.g., small electronics).

For complex products, liberation may begin with disassembly, but generally only for highly select items within that product that are: (1) very valuable and therefore worth the effort and resources to remove; (2) prohibited from further processing due to regulation or hazards; and/or (3) highly accessible and therefore efficient to remove. Instead, much of the liberation to recover usable parts or materials is then accomplished by dismantling as the main operation to separate identifiable pieces that can, for the most part, be readily disconnected but not necessarily into the product's original constituent parts. For example, large sections of a car may be cut apart with the intention to then later select and isolate specific components, or because that section is abundant in a particular material.

Dismantling therefore attempts to identify and isolate usable parts and materials while recognizing less-desirable items can be damaged and not reused. It is less costly, faster, and will probably be the selected operation in most end-of-life operations to separate materials for recovery rather than depending solely on the more idealistic process of disassembly [53,58,59]. Dismantling still enables a potentially significant degree of reuse and remanufacturing, which are higher goals than materials recycling for the circular economy. Conversely, reducing the size of materials only permits material recovery; while this is preferred to disposal in a landfill, it is really only the final option. However, dismantling practices can vary widely depending on local economy, regulations in the jurisdiction, and the business model of the dismantler [53,59].

After dismantling, materials are further liberated via shredding, grinding, crushing, or other common methods to further break apart the product remnants into smaller sizes. However, the wide application of modern plastics and joining mechanisms (e.g., adhesives, welding) have made recovery more difficult [58]. Shredding can break down a product into its component materials, but it will also likely leave behind unliberated particles that are "co-joined" materials. This unliberated fraction is impure (two or more materials remained fastened together) and will likely have little or no recovery value. As a result, a single operation such as shredding is unlikely to produce significant purity from modern materials, such as plastics [18].

As an alternative, implementing several unit operations could significantly improve the recovery of distinct materials that are joined. Prior research into applying cryogenic freezing to specimens made of joined, separate plastics [19] revealed the adhesive, which held fast under room temperature and shredding, did not hold under extreme cold. Cryogenic applications have been researched previously to improve materials recovery after size reduction [60]. Thus, augmenting the liberation operations with complementary treatments could improve the purity of recovered materials instead of relying on conventional, single operations.

3.5. Furniture

3.5.1. Recovery

Data on furniture waste in Canada is scarce, as furniture is not broken out as a separate category in the National Waste Characterization Report [61]. In the United States, 12.1 million tons of waste furniture was generated in 2018, accounting for 4.1% of all MSW, and only 0.3% of which was recycled [62]. The repair, refurbishment, and recycling of furniture are not conducted in large volumes, with direct reuse acting as the main circularity for furniture. In New York City, furniture accounts for approximately 80% by weight of products reused from online platforms [63].

3.5.2. Challenges to Recovery

Some challenges facing the remanufacture of furniture in Canada include decreased demand for value-retention processes (such as refurbishment or repair) due to the increased availability of low-cost new furniture, consumer perceptions of second-life products, and a lack of design for remanufacture [64].

A lack of convenient waste diversion options for furniture is a significant barrier to recovery. Furniture tends to be extremely bulky, which makes transportation and storage difficult. Many cities do offer special bulky item curbside collection services, but these programs typically are for items destined for landfill and do not facilitate recovery. Consumers with furniture items in a condition suitable for recovery are most often responsible for transporting the items themselves to a location for diversion. A recent survey from Habitat for Humanity Canada [65] indicates that Canadians are only half as likely to recycle household furniture as they are to recycle items like cans and paper (items that can be considered as some of the simplest products). A study of furniture at waste collection points in Germany [66] identified that 12% of furniture was in good condition and could be reused with little to no preparation of the items, with another 43% that could become eligible for reuse through systemic changes.

Furniture items are often made using variations of a few material types, such as wood, textiles, plastic, and metal components; for example, a wood cupboard with metal hinges and metal handles. Furniture is often more likely to be assembled using less-specialized components (such as screws), but is rarely designed for disassembly or remanufacture, which hampers higher value recovery operations.

4. Discussion—Understanding Issues of Recovery through Characteristics of Simple and Complex Products

4.1. Material Variability

The material variability ranges from the simplest in plastic food packaging, which contains at most a few, and often only one, type of plastic, to the most complex in a vehicle, which contains an enormous range of materials ranging from plastic foam in seats to complex electronic components. A challenge arising for complex products with high material variability is the range of material values contained in a single product. While there may be sufficient incentive to recycle or refurbish the more profitable materials, lower value or lower quality components are likely to become waste and could hamper overall recovery.

For simpler products, which may be made of only one material, the variability of materials used across products in the same application can pose a challenge to the sorting stage of recycling systems. This challenge of variability is also seen in more complex products at the component level, where lack of standardization complicates repairs and reuse.

The Ellen MacArthur Foundation [4] asserts that products with multiple parts are suitable for disassembly or refurbishment; this can alternately be described as increased material variability contributing to suitability for refurbishment, provided the level of material integration does not hinder this process.

4.2. Material Integration

Material integration ranges from the simplest products, where there is no integration due to the use of a single material (e.g., newsprint, boxboard), to complex products that contain many materials attached through various methods that cannot be separated by the average consumer. Furniture has some integration, such as nails, screws, and glue, that may be detachable, while industrial processes for separating tires into their constituent materials are well developed and widespread but rely on specific technologies. High levels of material integration pose challenges to recovery operations that require dismantling or the separation of materials, and can contribute to contamination concerns when materials cannot be sufficiently separated.

4.3. Material Complexity

Material complexity can range from the PET plastic in a single-use water bottle to the multiple rare metals used in high-end electronics. Products with a higher material complexity, in addition to higher material variability, may be more likely to be well suited to refurbishment and reuse because the materials selected tend to withstand longer use. However, given the high variability of complex goods, long-term durability is also likely to vary widely.

4.4. Product Form Factor

Products with an extremely simple product form factor (e.g., bottles, containers) should be relatively easy to capture, sort, and process through the available systems. Their simpler overall geometries and often identifiable shapes lend themselves to both manual and mechanical sorting processes that are already available. The challenge is often then moving them to reprocessors; such items typically need to be densified to ensure transporting them is economical.

Products with a more complex product form factor pose challenges to recovery, usually when attempting to identify recoverable materials and then disassembling them into pieces that can be manipulated for actual recovery. This challenge can be seen for small electronics (e.g., smartphones) or large items (e.g., vehicles), as previously discussed. Ironically, both small and large complex products can suffer from the same difficulty: accessing and removing valuable materials and parts economically. While there have been successes, the generally low rates of recovery noted previously belie the ongoing challenge of, for example, capturing precious metals from used electronics, or specific components deep within an automotive housing. While progressive engineering design is critical for all characteristics, its influence on product form factor and the implications for end-of-life recovery are perhaps the most profound.

4.5. Recovery Initiatives

Simpler recovery initiatives (e.g., curbside) result in a large regular volume of products collected for recovery, even when diversion is well below 100%, as seen in the case of plastic food packaging. Cell phones, which are not typically allowed in curbside collection but have a wide variety of convenient collection options, such as retail drop off, municipal drop off, and mail-back programs, also have recovery initiatives that are simple for consumers to access, but they require the preparation of the item on the part of the consumer (e.g., removing their personal data from the device), which hampers collection. Tires and vehicles have fewer locations for return due to their large and specialized nature, but do not require the same preparation, while there are often no clear recovery opportunities in place for furniture. Conversely, some items, such as furniture or vehicles, have their own opportunities for repair, refurbishment, or resale. Ensuring that secondary usage or recovery options are well communicated to consumers, and eliminating as many barriers as possible, can increase participation in recovery initiatives.

4.6. Simple vs. Complex Consumer Products Categorization

Based on the discussion and then applying Table 1 to the five example items—plastic food packaging; tires; smartphone; vehicle; and furniture—generates Table 2. In Table 2, each item is located along the spectrum and scored from 0 to 4. The scores (0, 1, 2, 3, 4) have no absolute meaning, and are used in this presentation to simply illustrate the conceptual relative difference between each item in each category. The score of 0 is not used because it is reserved for scenarios in which recovering material constituents operates at a fundamental level, such as the composting of organic wastes. Other scales for providing this broad comparison could also be valid.

Table 2. Aligning Example Items against Characteristics.

Characteristic	Simple Consumer Product	0	1	2	3	4	Complex Consumer Product
Material Variability (MV)	Single material with variations		Plastic food packaging	Furniture Tire	Cell phone	Vehicle	Multiple materials
Material Integration (MI)	None or weakly connected		Plastic food packaging		Furniture	Tire Cell phone Vehicle	Different materials strongly connected
Material Complexity (MC)	Basic materials		Plastic food packaging	Furniture	Tire Cell phone	Vehicle	Longer lasting, typically durable materials
Product Form Factor (PF)	Identifiable geometric configurations		Plastic food packaging Tire	Cell phone	Furniture	Vehicle	Highly variable, with unique configurations for specific needs
Recovery Initiatives (RI)	Common and convenience based		Plastic food packaging		Furniture Vehicle	Tire Cell phone	Dedicated facilities or specialized collection

The proposed evaluation system is designed to apply to a wide range of products. As previously described, it is not as complex or data intensive as other methods of assessing potential recovery that require a significant amount of detailed product information [14] or product specifications, such as a CAD model [67]. The vast majority of recycling measures in the literature require significant design effort (e.g., [16]), or more commonly, extensive studies from disassembly efforts (e.g., [13]). In addition, much of the existing literature focuses on specific products within select applications.

Instead, this system is meant to provide a starting point for designers at the early conceptual stages to consider the characteristics that contribute to or hinder recovery and identify how a given product compares to the continuum of products in our modern world. This can provide additional opportunities for creative design (e.g., fundamentally different alternatives for delivering what a product fulfills) by expanding the context. From there, more detailed analysis along the detailed methods already in the literature to consider any potential challenges can be conducted.

Table 2 identifies the approximate position of each item relative to that particular characteristic. The explanations that follow are generalizations, recognizing that there may be specific differences on a case-by-case basis.

- Plastic food packaging is scored as a "1" in every category. In general, such packaging is simple in form (e.g., bag, box-like, tray); usually only fabricated from a single material (e.g., PET); independent of any other material and not fastened to any other item; and easily recyclable if local curbside or depot containers permit.
- Furniture is scored as a "2" or "3" throughout. Furniture would have several materials (e.g., metal, wood, foam, fabric) but most furniture items would be relatively consistent from one to another; fastened together securely using typically screws or similar connectors but likely not using methods such as welding; relatively long lasting; comes in a variety of common geometric forms; and offers refurbishing options and even recovery but only arguably through dedicated channels (e.g., re-upholstery), otherwise items are likely landfilled.
- Tires range the gamut of scores from "1" to "4" and are an example of a product with a singular purpose that is not easily transferable to other applications. The tire shape is practically universal and simple compared to the vast majority of items; materials are generally limited (e.g., synthetic rubber, metal, or polymer belting) but are tightly formed together; and because of this arrangement, recovery is made through specialized recovery efforts.
- Cell phones are scored "3" to "4" with one exception in terms of form factor: cell phones have mostly settled into the typical rectangular shape. However, collecting, extracting, and recovering the precious metals from cell phones remain daunting challenges, and some components, such as the plastic casing, are unlikely to be recovered. There are also many accessories associated with cell phones that are unlikely to be recovered.
- Vehicles by their design, production, and use will prove among the most challenging, and are scored a "4" in almost all characteristics. Although much of the metal fraction is recovered, the non-metal fraction, which by absolute mass is significant, remains largely unrecovered and landfilled in many jurisdictions. However, it is scored as a "3" in terms of recovery because vehicles do offer some degree of repairability and can be resold, thus affording it some tangible recovery potential compared to, say, cell phones.

A graphic representation of the characteristic interactions with simple and complex products described in Table 2 can be seen in Figure 1 below. Each product characteristic exists on a scale from simplest, identified by points closest to the centre of the shape (score "0"), to most complex, identified by points at the outer edge of the shape (score "4"). Although the assessment is on a relative scale, this method provides a visual means for assessing a product's complexity, with a smaller area corresponding to a product that generally encounters fewer obstacles to actual materials recovery. This graphic can also be used to visually gauge the trade-offs between characteristics if proactively designing for materials recovery, by demonstrating how the shape coverage might vary if different characteristics are emphasized in alternative designs. For example, there may be an optimal combination of factors (e.g., simple RI; low to moderate MI; moderate to high MC) that engineers or designers could push towards to facilitate repair and refurbishment. Finally, it offers a graphical means to demonstrate the challenges of recovering complex products versus simple products.

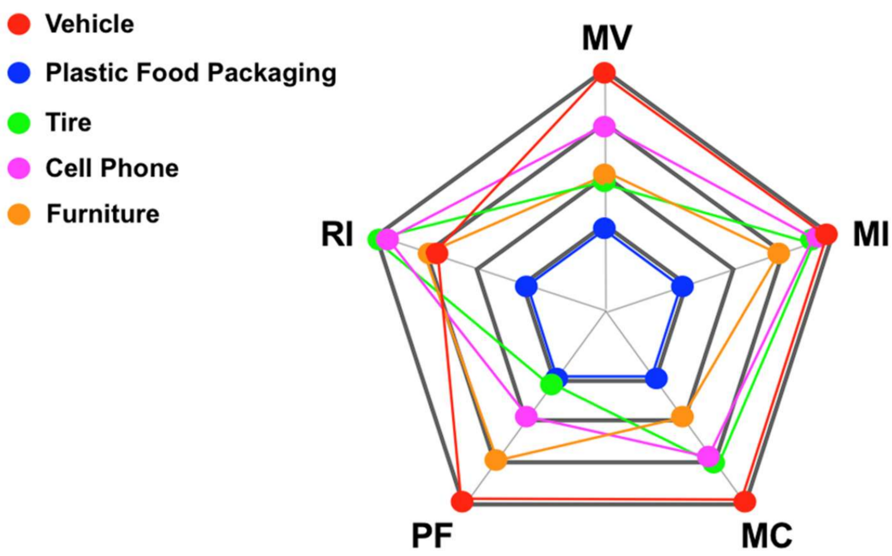

Figure 1. Graphical representation of characteristics: Material Variability (MV), Material Integration (MI), Material Complexity (MC), Product Form Factor (PF), and Recovery Initiatives (RI), contributing to product complexity. The centre is "0", with concentric rings from "1" to "4" (outermost boundary).

5. Conclusions—Supporting the Circular Economy

The first objective of this study presents an overview of the material challenges facing a variety of products. Although there are similar significant challenges facing the recovery of both simple and complex products, there are key differences, as illustrated by plastic food packaging, tires, cell phones, furniture, and vehicles. Therefore, it is critical to emphasize that recycling success varies significantly. These are just a few examples, highlighting the ways that complex products require more integrated and diverse solutions to improve recovery. To support the circular economy effectively, several key issues need to be addressed for both simple and complex product end-of-life management. These include:

- Encouraging and implementing harmonized simple product alternatives to better facilitate recycling. For example, while food companies must consider a mix of container characteristics (e.g., advertising, protection, cost) in deciding on food packaging, the sheer breadth of possible packaging risks overwhelming current recycling systems;
- Improving education to consumers and industries on what products are recyclable and how to recognize them. Despite decades of recycling practices, there is still confusion and even ignorance on what is recyclable for even the simplest products, such as plastic food packaging. Prior efforts include guidelines via print or online communication on what is or is not recyclable but households often question why one package is recyclable and yet another that is similar in appearance is not. Additional confusion can arise when consumers must prepare a product for recycling, such as removing data from a cell phone;
- Focusing on staged approaches or multiple operations for recovering materials from complex products. While disassembly may be ideal, it is arguably not as practical, nor as widespread. As illustrated in the discussion on automotive end-of-life recovery, the current practice is to have some form of dismantling, followed by size reduction. However, these approaches are often not systematically or consistently implemented, and there can be unintended losses through contamination or missed opportunities. A broader, phased approach to recovery could potentially address this;
- Improving on the removability of key components from complex products so that dismantling efforts can be optimized. This is particularly evident in a product such an automobile in which parts are often difficult to access. The industry should reconsider designing for improved dismantling to facilitate better recovery approaches and practices;

- Facilitating recovery efforts at the design stage could potentially enhance the efficiency and effectiveness of recovery operations. The characteristics comparison presented in Table 1 provides a starting point for a more robust consideration of the factors—other than focusing on the material type—that could affect recovery efforts from a design-for-recovery perspective.

The table and graphical presentations of the items, when compared against the potential characteristics of complexity, reveal the similarities and differences in product characteristics and identify the subsequent recovery challenges that will be encountered. More critically, this display enables designers and decision makers to consider trade-offs between characteristics when striving to increase the recovery of a material. Progress can focus on select aspects (e.g., material substitution) in the short term, with others (e.g., changing the overall design and form) being long-term goals. Overall, this arguably provides more guidance in design than generally asserting something needs to be made "more sustainable", particularly given the immense scope of products available to consumers and industries, and our largely stagnant recovery rates. This achieves the second objective of the study: to establish how the classification concept of simple and complex products can be beneficial in describing a given product and its material recovery prospects and challenges.

Although the prior discussion focused on five product examples, many of the issues apply to other similar products (e.g., retail goods, appliances, clothing). While simple products and complex products share some recovery challenges, it is critical to address their many differences. The suggested approach here strives to advance how recovery can be interpreted beyond the simplistic messaging associated with the important but common curbside recycling efforts. Again, the presentation here is not prescriptive: there may be other legitimate characteristics and ensuing interpretations. Instead, it is an illustrative means to demonstrate how considering product characteristics can improve the understanding of, and decisions made for, product design, production, use, and recovery. Addressing the issues highlighted in this paper will ultimately enhance recovery, which remains a key component in the shift towards a circular economy.

Author Contributions: The authors contributed to this manuscript as follows: research, analysis, and writing (original draft preparation)—C.J.; formal analysis, writing (review and editing)—K.S.; formal analysis and writing (review and editing)—S.S.-B.; formal analysis—A.S.; conceptualization, funding, supervision, and original draft preparation—E.T. All authors have read and agreed to the published version of the manuscript.

Funding: This manuscript was based in part on research funded by the AUTO21 Network Centres of Excellence (Canada) and the Natural Sciences Research Council of Canada (NSERC).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: The authors would like to thank the support by David Gold and Standard Auto Wreckers, and Steven Fletcher and the Ontario Automotive Recyclers Association (OARA).

Conflicts of Interest: The authors declare no conflict of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

References

1. Brown, B.J.; Hanson, M.E.; Liverman, D.M.; Merideth, R.W. Global sustainability: Toward definition. *Environ. Manag.* **1987**, *11*, 713–719. [CrossRef]
2. Kirchherr, J.; Reike, D.; Hekkert, M. Conceptualizing the circular economy: An analysis of 114 definitions. *Resour. Conserv. Recycl.* **2017**, *127*, 221–232. [CrossRef]
3. Bringezu, S.; Ramaswami, A.; Schandl, H.; O'Brien, M.; Pelton, R.; Acquatella, J.; Ayuk, E.; Chiu, A.; Flanegin, R.; Fry, J.; et al. Assessing Global Resource Use: A Systems Approach to Resource Efficiency and Pollution Reduction. 2017. Available online: https://wedocs.unep.org/handle/20.500.11822/27432 (accessed on 27 October 2020).

4. Ellen MacArthur Foundation. Towards the Circular Economy. 2013. Available online: https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf (accessed on 23 November 2019).
5. Environment and Climate Change Canada. Canadian Environmental Sustainability Indicators: Solid Waste Diversion and Disposal. 2017. Available online: https://www.canada.ca/en/environment-climate-change/services/environmental-indicators/solid-waste-diversion-disposal.html (accessed on 27 October 2020).
6. Qu, S.; Guo, Y.; Ma, Z.; Chen, W.Q.; Liu, G.; Wang, Y.; Xu, M. Implications of China's foreign waste ban on the global circular economy. *Resour. Conserv. Recycl.* **2019**, *114*, 252–255. [CrossRef]
7. Hahladakis, J.N.; Iacovidou, E. An overview of the challenges and trade-offs in closing the loop of post-consumer plastic waste (PCPW): Focus on recycling. *J. Hazard. Mater.* **2019**, *380*, 120887. [CrossRef]
8. De Decker, K. How Circular is the Circular Economy? *Low-Tech Mag.* **2018**, *3*, 1–7. Available online: https://www.lowtechmagazine.com/2018/11/how-circular-is-the-circular-economy.html (accessed on 27 October 2020).
9. Reuter, M.; van Schaik, A.; Ballester, M. Limits of the circular economy: Fairphone modular design pushing the limits. *World Metall.* **2018**, *71*, 68–79.
10. EPA. Nondurable Goods: Product-Specific Data. 2020. Available online: https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/nondurable-goods-product-specific-data (accessed on 22 September 2020).
11. EPA. Durable Goods: Product-Specific Data. 2020. Available online: https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/durable-goods-product-specific-data (accessed on 22 September 2020).
12. WRAP. *Recyclability Efficiency Metric: Development of Options for Setting Client Procurement Requirements for Recyclability in Construction Projects*; WRAP: Banbury, UK, 2008.
13. Vanegas, P.; Peeters, J.R.; Cattrysse, D.; Tecchio, P.; Ardente, F.; Mathieux, F.; Dewulf, W.; Duflou, J.R. Ease of disassembly of products to support circular economy strategies. *Resour. Conserv. Recycl.* **2018**, *135*, 323–334. [CrossRef] [PubMed]
14. Ellen MacArthur Foundation; Granta Design. Circularity Indicators: An Approach to Measuring Circularity Methodology. 2019. Available online: https://ellenmacarthurfoundation.org/material-circularity-indicator (accessed on 9 September 2020).
15. Cayzer, S.; Griffiths, P.; Beghetto, V. Design of indicators for measuring product performance in the circular economy. *Int. J. Sust. Eng.* **2017**, *10*, 289–298. [CrossRef]
16. Roithner, C.; Cencic, O.; Rechberger, H. Product design and recyclability: How statistical entropy can form a bridge between these concepts—A case study of a smartphone. *J. Clean. Prod.* **2022**, *332*, 129971. [CrossRef]
17. Sultan, A.A.M.; Lou, E.; Mativenga, P.T. What should be recycled: An integrated model for product recycling desirability. *J. Clean. Prod.* **2017**, *154*, 51–60. [CrossRef]
18. Tam, E.; Jekel, L. Separation and liberation factors in designing for automotive materials recovery. *SAE Tech. Pap.* **2004**. [CrossRef]
19. Noor-A.-Faiza, B. Liberating Plastics from Commercial Plastic Products and the Potential Benefits of Pre-Conditioning. Master's Thesis, University of Windsor, Windsor, ON, Canada, 2008.
20. Almoslehy, S.A.M.; Alkahtani, M.S. Key approaches, risks, and product performance in managing the development process of complex products sustainably. *Sustainability* **2021**, *13*, 4727. [CrossRef]
21. Tam, E.; Soulliere, K.; Sawyer-Beaulieu, S. Managing complex products to support the circular economy. *Resour. Conserv. Recycl.* **2019**, *145*, 124–125. [CrossRef]
22. Deloitte; Cheminfo Services Inc. Economic Study of the Canadian Plastic Industry, Markets and Waste: Summary Report to Environment and Climate Change Canada. 2019. Available online: https://publications.gc.ca/site/eng/9.871296/publication.html (accessed on 29 January 2020).
23. Government of Canada. Ocean Plastics Charter. 2018. Available online: https://www.canada.ca/content/dam/eccc/documents/pdf/pollution-waste/ocean-plastics/Ocean%20Plastics%20Charter_EN.pdf (accessed on 22 April 2020).
24. Iacovidou, E.; Velenturf, A.P.M.; Purnell, P. Quality of resources: A topology for supporting transitions towards resource efficiency using the single-use plastic bottle example. *Sci. Total Environ.* **2018**, *647*, 441–448. [CrossRef]
25. Environment and Climate Change Canada. Government of Canada Moving Forward with Banning Harmful Single-Use Plastics. 2021. Available online: https://www.canada.ca/en/environment-climate-change/news/2021/12/government-of-canada-moving-forward-with-banning-harmful-single-use-plastics0.html (accessed on 22 December 2021).
26. Environmental Protection Act, Ontario Regulation 101/94 Recycling and Composting of Municipal Waste. 2011. Available online: https://www.ontario.ca/laws/regulation/940101 (accessed on 29 January 2020).
27. Lindsay, D. Renewing the Blue Box: Final Report on the Blue Box Mediation Process. 2019. Available online: https://www.ontario.ca/page/renewing-blue-box-final-report-blue-box-mediation-process (accessed on 23 November 2019).
28. Saxe, D. *Beyond the Blue Box: Ontario's Fresh Start on Waste Diversion and the Circular Economy*; Environmental Commissioner of Ontario: Toronto, ON, Canada, 2017.
29. World Economic Forum, Ellen MacArthur Foundation, & McKinsey & Company. The New Plastics Economy: Rethinking the Future of Plastics. 2016. Available online: http://www.ellenmacarthurfoundation.org/publications (accessed on 20 April 2020).
30. Kelleher Environmental. CIF Project #772 Diversion vs. Net Cost Analysis for the Ontario Blue Box System. 2014. Available online: https://thecif.ca/projects/documents/722-Final_Report.pdf (accessed on 9 February 2020).
31. Chung, E. Your Lifestyle is Making Blue Box Recycling Unsustainable. CBC News. 27 March 2018. Available online: https://www.cbc.ca/news/technology/recycling-blue-box-challenges-evolving-tonne$-$1.4584484 (accessed on 25 February 2020).

32. Ignatyev, A.; Thielmans, W.; Vander Beke, B. Recycling of polymers: A review. *ChemSusChem* **2014**, *7*, 1579–1593. [CrossRef] [PubMed]
33. Geueke, B.; Groh, K.; Muncke, J. Food packaging in the circular economy: Overview of chemical safety aspects for commonly used materials. *J. Clean. Prod.* **2018**, *193*, 491–505. [CrossRef]
34. Lakhan, C. Diversion, but at what cost? The economic challenges of recycling in Ontario. *Resour. Conserv. Recycl.* **2015**, *95*, 133–142. [CrossRef]
35. Industry Council for Packaging & the Environment. Factsheet: Too Much Packaging? 2018. Available online: https://www.incpen.org/too-much-packaging/ (accessed on 25 October 2020).
36. Canadian Association of Tire Recycling Agencies. Annual Report 2020. 2021. Available online: https://www.catraonline.ca/news (accessed on 9 November 2021).
37. World Business Council for Sustainable Development. Global ELT Management—A Global State of Knowledge on Collection Rates, Recovery Routes, and Management Methods. 2018. Available online: https://www.wbcsd.org/Sector-Projects/Tire-Industry-Project/End-of-Life-Tires-ELTs (accessed on 23 July 2021).
38. Daystar, J.; Golden, J.; Handfield, R.; Woodrooffe, J. *Retread Tires in the U.S. and Canada: An Analysis of the Economic & Environmental Benefits for Fleet Operators and the U.S. Government*; Bridgestone Bandag, LLC: Nashville, Tennessee, 2018.
39. European Tyre & Rubber Manufacturers' Association. End-of-Life Tyre Report 2015. 2015. Available online: https://www.etrma.org/news-resources/library/ (accessed on 29 July 2021).
40. European Tyre & Rubber Manufacturers' Association. ETRMA Contribution to the RAC/SEAC Opinion on an Annex XV Dossier Proposing Restrictions on Intentionally-Added Microplastics. 2020. Available online: https://www.etrma.org/news-resources/library/ (accessed on 31 August 2021).
41. Forti, V.; Baldé, C.P.; Kuehr, R.; Bel, G. The Global E-Waste Monitor 2020: Quantities, Flows and the Circular Economy Potential. 2020. Available online: http://ewastemonitor.info/ (accessed on 11 November 2021).
42. Canadian Radio-television and Telecommunications Commission. Communications Monitoring Report. 2020. Available online: https://publications.gc.ca/site/eng/9.506067/publication.html (accessed on 10 November 2021).
43. Noman, R.; Amin, S.H. Characteristics of cellphone reverse logistics in Canada. *J. Remanufacturing* **2017**, *7*, 181–198. [CrossRef]
44. Statistics Canada. *Table 38–10−0126–02 Household Hazardous Waste, eWaste*; Statistics Canada: Ottawa, ON, Canada, 2021.
45. World Economic Forum. *A New Circular Vision for Electronics: Time for a Global Reboot*; World Economic Forum: Geneva, Switzerland, 2019.
46. Baldé, C.P.; Forti, V.; Gray, V.; Kuehr, R.; Stegmann, P. The Global E-waste Monitor 2017. 2017. Available online: http://ewastemonitor.info (accessed on 11 November 2021).
47. Statistics Canada. Table 11–10−0236–02 Retail Sales of Motor Vehicles. In *Automotive Products and Services, Inactive (×1000)*; Statistics Canada: Ottawa, ON, Canada, 2019. [CrossRef]
48. Duranceau, C.; Sawyer–Beaulieu, S. *Vehicle Recycling, Reuse, and Recovery: Material Disposition from Current end-of-Life Vehicles. Technical Paper Series*; World Congress: Detroit, MI, USA, 2011.
49. European Union. *Directive 2000/53/EC of the European Parliament and of the Council of 18 September, 2000 on End-of-Life Vehicles*; Publications Office of the European Union: Luxembourg, 2000.
50. European Union. Commission Decision of 27 June, 2002 Amending Annex II of Directive 2000/53/EC of the European Parliament and of the Council on End-of-Life Vehicles. In *2002/525/EC*; Publications Office of the European Union: Luxembourg, 2002.
51. Statistics Canada. Table 20–10−0001–01 New Motor Vehicle Sales. 2018. Available online: https://www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=2010000101#timeframe.htm (accessed on 11 June 2018).
52. Statistics Canada. 2018. Statistics Canada Table 23–10−0067–01 Vehicle Registrations, by Type of Vehicle. 2018. Available online: https://www150.statcan.gc.ca/t1/tbl1/en/cv.action?pid=2310006701 (accessed on 29 January 2020).
53. Sawyer-Beaulieu, S. Gate-to-Gate Life Cycle Inventory Assessment of North American End-of-Life Vehicle Management Processes. Ph.D. Thesis, University of Windsor, Windsor, ON, Canada, 2009.
54. Day, M.; Graham, J.; Lachmansingh, R.; Chen, E. Characterization of auto shredder residue—A Canadian perspective. *Resour. Conserv. Recycl.* **1993**, *9*, 255–279. [CrossRef]
55. Tchobanoglous, G.; Theisen, H.; Vigil, S.A. *Integrated Solid Waste Management: Engineering Principle and Management Issues*; McGraw Hill Inc.: New York, NY, USA, 1993.
56. Mesa, J.; Esparragoza, I.; Maury, H. Development of a metric to assess the complexity of assembly/disassembly tasks in open architecture products. *Int. J. Prod. Res.* **2018**, *56*, 7201–7219. [CrossRef]
57. Soh, S.L.; Ong, S.K.; Nee, A.Y.C. Design for assembly and disassembly for remanufacturing. *Assem. Autom.* **2016**, *36*, 12–24. [CrossRef]
58. Soo, V.K.; Compston, P.; Doolan, M. The influence of joint technologies on ELV recyclability. *Waste Manag.* **2017**, *68*, 421–433. [CrossRef] [PubMed]
59. Cheminfo Services Inc. *Study of the End-of-Life Vehicle Recycling and Management Sector in Canada. Project # 529–2013, Prepared for the Canadian Council of Ministers of the Environment (CCME) End-of-Life Vehicles Task Group (ELVTG)*; Cheminfo Services Inc.: Markham, ON, Canada, 2021.
60. Gente, V.; Marca, F.; Lucci, F.; Massacci, P.; Pani, E. Cryo-comminution of plastic waste. *Waste Manag.* **2004**, *24*, 663–672. [CrossRef] [PubMed]

61. Environment and Climate Change Canada. National Waste Characterization Report: The Composition of Canadian Residual Solid Waste. 2020. Available online: https://publications.gc.ca/site/eng/9.884760/publication.html (accessed on 15 November 2021).
62. USEPA. Advancing Sustainable Materials Management: 2018 Tables and Figures. 2020. Available online: https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/advancing-sustainable-materials-management (accessed on 15 November 2021).
63. Lugo, M.; Ail, S.S.; Castaldi, M.J. Approaching a zero-waste strategy by reuse in New York City: Challenges and potential. *Waste Manag. Res.* **2020**, *38*, 734–744. [CrossRef] [PubMed]
64. National Zero Waste Council. *Waste Prevention: The Environmental and Economic Benefits for Canada*; National Zero Waste Council: Vancouver, BC, Canada, 2021.
65. Habitat for Humanity Canada. When it Comes to Household Furniture—Donate, Don't Ditch. 2021. Available online: https://habitat.ca/en/news/press-releases (accessed on 15 November 2021).
66. Messmann, L.; Boldoczki, S.; Thorenz, A.; Tuma, A. Potentials of preparation for reuse: A case study at collection points in the German state of Bavaria. *J. Clean. Prod.* **2019**, *211*, 1534–1546. [CrossRef]
67. Fang, H.C.; Ong, S.K.; Nee, A.Y.C. Product remanufacturability assessment based on design information. *Procedia CIRP* **2014**, *15*, 195–200. [CrossRef]