# Practitioner's Section

## Challenges and opportunities in the sustainability of communication devices – an operator perspective exemplified by Deutsche Telekom AG

Steffen Wasmus* and Marius Chofor Asaba**

* Deutsche Telekom AG, Landgrabenweg 151, 53227 Bonn, Germany, steffen.wasmus@telekom.de
** Institute of Energy and Climate Research (IEK), Institute of Business Administration at the DEP of Chemistry and PharmacyLeonardo-Campus 1, 48149 Münster, Germany, m.chofor.asaba@fz-juelich.de

*DOI: 10.17879/64159699759 ; URN: urn:nbn:de:hbz:6-64159702168*

Considering that the communication devices (CD) segment only makes up just 7% of the yearly electrical and electronic equipment (EEE) waste, this means that there are no specific CD related sustainable measures, but just EEE generalized solutions. As such, this paper aims at exploring the critical factors for improving the sustainability as well as for the possible implementation of Circular Economy (CE) strategies for the CD segment along their entire supply chain. A wide range of factors pertaining to sustainability in the supply chain especially regarding the electrical and electronic equipment (EEE) market was gotten by means of an elaborate literature analysis. The factors are then compared to the present practices of the revenue leading telecommunications company in Europe, Deutsche Telekom AG (DTAG). From the literature review, we discovered a range of solutions a CD provider such as DTAG can use to improve the sustainability of its CD portfolio over the entire life cycle. These included ensuring that not only the communication company, but all the various suppliers follow sustainable practices such as Green Supply Chain Management or Closed Loop Supply Chain practices, and that they abide to the set of legislations and standardizations already in place for EEE such as REACH, RoHS, ISO 14004 and EPR. Good sustainable practice is also important, including the swapping of the present technologies for more sustainable ones and ensuring that SDGs are meet in the long run. Most of these methods and practices are already being implemented by the DTAG as part of their global strategy. In addition to an insight on the various concepts this industry should follow to ensure adequate implementation of CE, the study further provides suggestions as to strategies which could improve the sustainability of CDs.

## 1 Introduction

One of the authors is responsible for the quality and sustainability of DTAG's mobile device portfolio in Europe, therefore the study will focus on small Communication Devices (CDs).

### 1.1 Present state of the sustainability of communication devices

CDs are ubiquitous in our modern digital world and include smartphones, routers, media receivers, data sticks and many other subcategories. Normally, relatively small when compared to appliances but having very large annual production figures (e.g. 1.4 bill.

smartphones in 2018) (Reith et al. (2019)), the environmental impact of CDs is widely discussed in the public.

Cook and Jardim (2017) investigated the impact of the manufacture of electronic devices, particularly smartphones, onto the environment, with focus on the areas of energy consumption, resource consumption and hazardous chemicals. Albeit acknowledging that the major brands have made some progress in their voluntary sustainability commitments, the authors see massive environmental issues associated with electronic manufacturing. Root cause for several of those is the long and non-transparent supply chain. Other issues found by the authors are dirty energy, mounting electronic waste, little use of post-consumer material and substitution objectives for hazardous chemicals are not ambitious enough. Cook and Jardim (2017) cite another study according to which smartphones and other electronic devices are among the most resource intensive: for each 100g minerals required for a smartphone 34kg of rock must be mined. In addition, the contribution to the greenhouse gas emissions is seen critical as 80% of such emissions during a smartphone lifecycle is allotted to its production. Consequently, the authors request more responsibility for the supply chain (SC), design for sustainability and better strategies for end-of-life. For instance, their request for design for sustainability includes the elimination of hazardous chemicals and the use of recyclable material.

Dziamski et al. (2014) did a similar study nearly on the same device category already a few years earlier choosing climate protection, ecology and labor conditions as focus areas. The author came to the same conclusion as Cook and Jardim (2017) that the industry has significant sustainability issues, with both studies coinciding on several of these issues.

These two studies clearly suggest the need to make the CD business more sustainable. Leverages are to increase the utilization period and to introduce circular economy into the business. Revellio and Hansen (2017) looked into different strategies to implement circular economy into the smartphone industry. They conclude that there are functioning value creation architectures to achieve that. The important conclusion for the scope of this publication, though, is that smartphone design practices have a direct impact on the coordination efforts of the involved parties.

Stobbe et al. (2017) had a detailed look into smartphone design practices paying into the sustainability, in particular, durability, reparability and factorability for recycling. The authors identified different smartphone design practices and evaluated their advantages and disadvantages in the light of the above criteria. They have concluded that neither one is ideal with respect to sustainability. In particular, the use of glue in the smartphone assembly is seen as critical as it renders disassembly more difficult. It may even become dangerous if the Li-ion battery is glued in and its removal leads to a rupture of the pouch into which the Li-ion battery is sealed. This raises the question whether the use of glue is a good idea at all. However, there are many smartphone types with IP certification (dust and/or liquid proof) as well as a strong relevance of the aesthetic appearance as purchasing criteria for prospective customers. Both of which seems to render a substitution of gluing by other fastening methods as not realistic in the foreseeable future. This makes it necessary to look at the properties of the glues for smartphones and other CDs. Stobbe et al. (2017) also see that there are certain critical materials in smartphones in need of substitution by less critical alternatives. The authors have made a large number of proposals on how to design smartphones in a more sustainable way.

As of now, some major players in the smartphone industry already make use of some of these sustainable design practices, but there is certainly room to further implement more of such sustainable design practices. CDs are part of the consumer electronics which in general is relatively price-sensitive. This may help to explain why so far not more of such sustainable design practices are implemented. Other reasons may be a lack of suitable base materials that may either not be available at all or not available in the right amounts or at the right price point. Another reason is certainly the frequently non-transparent SC, as criticized by Cook and Jardim (2017), which in many cases may not allow component selection conscious of sustainability criteria. This may be compounded by difficulties to assess sustainability information on the side of some players in the electronic industry.

Looking at all those leverages to make the CD industry more sustainable would easily exceed the scope of this publication. There is agreement in the literature that harmful substances and a lack of sufficiently high amounts of post-consumer materials are relevant and significant issues. Both issues need to be solved mainly by improving the choice of materials. Hence, this publication will focus subsequently on the materials used for CDs. This is where Deutsche Telekom AG (DTAG) sees a benefit to initiate a dialogue and cooperation across the SC including the chemical industry which as a base material supplier has an important role in making CDs more sustainable.

## 1.2 The role of the supply chain

CDs are a product of a long supply chain which in a very high-level view is spanning from mines and crude oil wells, continuing with refineries and smelters, thence the refinery and smelter products are manufactured into base materials, these are turned into components, and finally these are assembled into completed CDs. This involves a lot of companies from several industries and therefore it is no surprise that Cook and Jardim (2017) bewail a non-transparent SC. In many of those SC stations the chemical industry plays an important role. Nevertheless, sustainability cannot be just considered from the perspective of the completed CD in isolation, but also needs to take all sustainability effects along the SC into account. This in turn implies that responsibility does not end at the company door but includes shared responsibilities with neighboring parties in the SC.  In addition, there is another SC involved after usage of CDs which includes companies for collecting, disassembly and material recovery. In addition, the impacts onto that SC must be taken into the consideration.

Kim and Davis (2016) state in their study on Global SC Sustainability after an analysis of the SEC reports of the use of conflict material, the reports from over 1300 corporations showed that 80% of them admitted to being unable to determine the origin if the minerals, with only 1 % being able to certify themselves free of conflict materials. It is also mentioned that those less likely to declare their products conflict-free were firms, which are internationally diversified as well as the large ones with vastly dispersed SCs. Reason being that complexity reduces the transparency of the SC.

### 1.2.1 Sustainability x supply chain

Many companies have in recent decades adopted the shift towards environmental management as a key strategy to ensure a long-lasting organizational performance as well as retain advantages on global markets. This is a result of the creation of environmental standards as well as regulations by the governments, coupled with the customers' own self-awareness towards sustainability (Genovese et al., 2010). In order to achieve the highest success at the lowest possible cost, it is necessary to optimize along the entire SC (Handfield et al., 2002). The SC considers a product from the initial raw materials processing until delivery to customer, focusing here is a valuable option for wider adoption and development of sustainability. A study carried out by Linton et al. (2007) states that it is necessary to broaden the scope of the SC to consider and include issues and flows which go beyond the core of SC management, such as: product design, manufacturing by-products, by-products produced during product use, product life extension, product end-of-life, and end-of-life recovery processes (Linton et al., 2007). This view ensures that focus on environmental management and operations is shifted from just locally optimizing the environmental factors but also considering the entire SC during production, consumption, customer service and post-disposal disposition of products.

### 1.2.2 Green supply chain management

Going through literature there are quite a handful of studies addressing the issue of implementing sustainable supply chain management (SCM) practices in the electronics industry. Although the specifics of these studies do not directly address the CDs as of such, the findings can without doubt be considered for the CDs as highly relevant, seeing as they make up a large share of the consumer electronics' market. In the Table 1 (Kumar et al., 2017) below, we see that the CDs make up 7% of the yearly waste, which amounts to about 3 million tons.

With that in mind, the electronic device sector as well as the electrical industry on a whole have seen many changes to the SCM practices in the last decades. The most noticeable sustainable practice is that of implementing of green supply chain management (GSCM) prac-

Table 1 Varying WEEE Categories (source: Kumar et al., 2017).

| Categories | Amount (million tons) |
|---|---|
| Temperature exchange equipment | 7.0 |
| Screens & monitors | 6.3 |
| Lamps | 1.0 |
| Large Equipment | 11.8 |
| Small equipment | 12.8 |
| Small IT and telecommunication equipment | 3.0 |

tices relative to European Union directives (European Union, 2003). The aim of GSCM is to enable enterprises to achieve profit and market share objectives by reducing the environmental risk and impact (van Voek, 2013).

### 1.2.3 Internal environmental management

This is necessary for improving the enterprise's environmental performance (Melnyk et al. 2003). Of importance here is the support of those at the top of the hierarchy structure, the senior managers, as it is necessary and can be said to be a key driver to achieve a successful adoption and implementation of most innovations, technology, programs and activities (Hamel and Prahalad, 1989).

### 1.2.4 External GSCM practices

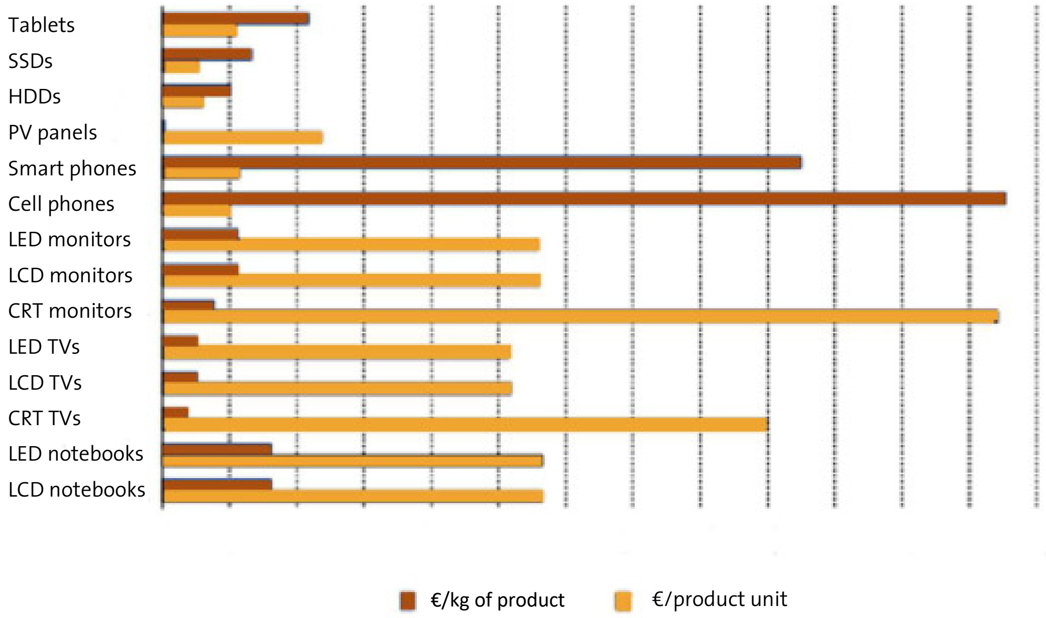
On the top of the list of external GSCM practices is the green purchasing. In order for a company to achieve maximum economic performance while at the same time minimizing the negative environmental effects, it needs to ensure that the SC is green by choosing green suppliers (Chou et al., 2016). Certain key factors need to be met for this to be adequately implemented such as providing design specification to the suppliers that includes environmental requirements for purchased items, cooperation with suppliers for environmental objectives, environmental audits for supplies' internal management, and suppliers' ISO 14001 certification (Chen et al., 2016). It is necessary that large companies exert pressure on their suppliers as well ensure that the practices of second tier suppliers are environmentally friendly (Zhu et al., 2008).

## 1.3 Legislations and Standardizations

Disposal of waste electrical and electronic equipment (WEEE) is a serious topic as about 30 -50 million tons of WEEE are deposited each year globally, with an estimation growth rate of 3-5 % (Afroz et al., 2013). This amounts to about 5,9 kg/inhabitant (Balde et al., 2017). Various substances exist within these wastes, which are critical, valuable and hazardous, and as such require a dedicated recycling process to avoid not just environmental and health issues, but also resource related issues (Cucchiella et al., 2015).

With this idea of the need to achieve sustainable development, the European Union (EU)'s WEEE directive came into force in August 2004, which requires that manufacturers and importers take back the used products from consumers and ensure that these are environmentally friendly recycled (Widmer et al., 2005). Coupled with this is another directive of interest to the field of electronic and electrical devices is the EU's restriction of hazardous substances (RoHS) which prohibits the use of regulated hazardous substances in the products viz. lead, cadmium, mercury, hexavalent chromium, polybrominated biphenyls (PBBs) and polybrominated diphenyl ethers (PBDEs) (Wright and Elcock, 2006). The intent of both directives is the reduction of the problems associated with management of heavy metals and flame-retardants found in electrical and electronic equipment. The directives go a step forward to ensure that consumer awareness is increased by ensuring that producers label each piece of electrical or electronic equipment based on the appropriate disposal method before it hits the market. There also exists WEEE directive (2012/19/EU) aimed at the

**Figure 1 Electronic Waste Streams for potential revenue (source: Cucchiella et al., 2015).**



end of life management of wastes from electric and electronic equipment. Other EU compliance strategies exist which ensure that sustainable products are marketed in a transparent way. These include the energy-using products (EuP) regulation - with focus on the entire life cycle of products design, manufacture, use, and disposal, and the registration, evaluation, and authorization of chemicals (REACH) requirements – which requires that manufactures list all chemical ingredients contained, explain how they are used and include a toxicity assessment (European Commission, 2006).

Apart from the EU's set of compliances, there also exist standards aimed at ensuring the production of sustainable products. For example, the international organization for standardization's ISO 14001 standard has become the main reference in the field of corporate environmental management and with more than 300,000 organizations worldwide having adopted this standard it sees a yearly increase in adoption of about 10% (Boiral et al., 2018). Another instrument worth mentioning is that of the Organization for Economic Co-operation and Development (OECD), which entails that producers are given a significant responsibility, either financial and/or physical regarding post-consumer products, meaning that producers need to develop a sustainable reverse SC for the treatment or disposal of post-consumer products – named extended producer responsibility (EPR) (OECD, 2017).

### 1.4 The situation regarding materials

As mentioned before WEEE is rapidly growing and as such, it is necessary that this be adequately managed. With the expectation that the WEEE stream will gradually increase over the next years it is as such necessary to set up measures to deal with waste in this sector.

In their study on WEEE, Kumar et al. (2017) mention the three main benefits WEEE recycling brings about viz. economic, environmental and human health benefits.

On the level of economics, not only does material recovery offer better opportunities, it also offers a potential revenue stream (Figure 1) because the amount of scare resources mined will be reduced as well as job opportunities such as WEEE recyclers will emerge (Cucchiella et al, 2015; Heacock et al., 2016).

The environmental benefits here include reducing the amount of hazardous waste in the landfills as well as tackling issues like greenhouse gas emissions through energy savings (Cui and Forssberg, 2003). As for the human health benefits the damages related to the materials used in CDs is discussed in the subchapter below - "Materials for electronic components".

### 1.5 Technical polymers

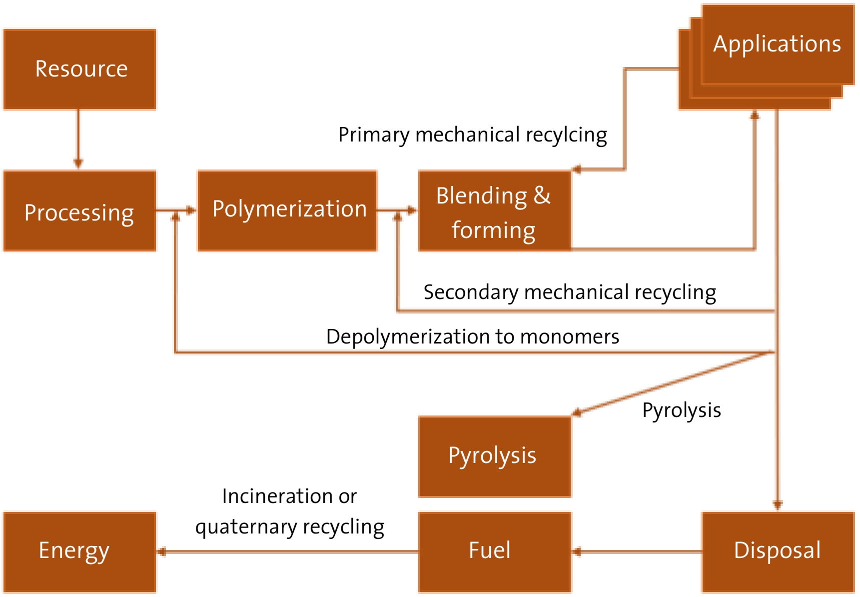
With the ever increasing and varying needs of end consumer products, the production of synthetic polymers is expected to triple by 2050 form over 311 million tons in 2014 (Hong and Chen, 2017). This leads to the problem of sustainability seeing as the vast majority of synthetic polymers are not designed for degradability and recyclability but for performance and durability (Jambeck et al., 2015). In their study on sustainability regarding the recycling of polymers, Hong and Chen (2017) mention three methods existing for the disposal of polymer waste: burying them in landfills, incineration for energy recovery, and mechanical recycling, with both landfilling and incineration lead to serious environmental issues with little or no material recovery. As for mechanical recycling, this method has been considered a temporary solution involving sorting, washing and drying postconsumer polymer products and thereafter these are melted into new polymer material (Ignatyev et al., 2014). Nonetheless, with this method there is the issue of moisture, residual catalyst and various contaminants, which exist in the polymer waste during the second melting process. Coupled with the issue that mechanical recycling is not adequate for colored polymer products due to various additional issues, this means that large majorities of polymers end up one way or the other in landfills or are incinerated.

There also exists the issue of the type of resources used in the polymer production. The production of the polymers is mainly petroleum -based and this brings about the problem of increased energy demand as well as the issue of recycling the enormous growth of disposed polymer wastes over the past few decades has brought (Moore, 2008). As such, there is need to replace these with more sustainable polymers from renewable resources.

### 1.6 Materials for electronic components

In Table 2 (Kumar et al., 2017) below, we see global sales data for various electronic devices. The life expectancies of these various devices as

Figure 2 Most common polymer recycling methods (source: Ignatyev, Thielemans, & Vander Beke, 2014)



seen in Table 3 (Ely, 2014; Kumar et al., 2017) goes to show that the most sold electronic devices are CDs. With the rapid change in the industry and technological advancements, the replacement period of CDs is very short, leading to older technologies eventually ending up in the waste streams.

Stobbe et al. (2017) clearly have pointed out that smartphones consist of a vast diversity of components and materials. Particularly trace elements are a problem. In a study from 2014, Beverley et al. (2014) analyzed a number of phones and came up with a list of 83 elements detected in some or all of them. These were: Be, B, Mg, Al, Ti, V, Mn, Fe, Co, Ni, Cu, Zn, As, Se, Y, Nb, Pd, Ag, In, Sn, Sb, Te, Ba, Ta, W, Pt, Au, Tl, Pb, Bi, Pr, Nd, Sm, Eu, Gd, Tb, Dy, and Er. Present in this list are the Group IV and V trace elements vanadium, aluminum, gold and lead, which are all toxic to the human body and should be avoided landing in landfills (Prashanth et al., 2015).

In addition, an article on the effects of improper recycling of toxins present in cellphones

**Table 2 Varying WEEE Categories (source: Kumar et al., 2017).**

| Items | Units (million) |
|---|---|
| Android phones | 1675.45 |
| iPhone 6 | 19.75 |
| Total smartphone | 12,444.89 |
| Laptop & desktop | 238.5 |
| LCD TV | 5.79 |
| Plasma TV | 0.63 |
| CRT TV | 0.55 |
| Total TV | 7.08 |
| Printer | 106,000 |
| e-book reader | 20.2 |
| Home appliances | 583 |
| Electric ovens | 0.733 |
| Refrigerators | 11.13 |
| Automatic washers | 9.68 |

**Table 3 Lifespan Estimation for Electric and Electronic Equipment (source: Ely, 2014; Kumar et al. 2017).**

| Items | Units (million) |
|---|---|
| Flat panel TV | 7.4 |
| Digital camera | 6.5 |
| DVD player or recorder | 6.0 |
| Desktop computer | 5.9 |
| Blu-ray player | 5.8 |
| Video game console | 5.7 |
| Laptop/notebook | 5.5 |
| Tablet | 5.1 |
| Cellphones (not smartphones) | 4.7 |
| Smartphones | 4.6 |

was published by the global recycling company e-Cycle. The presence of harmful elements like lead, mercury, arsenic, cadmium, chlorine and bromine is mentioned which can leak into groundwater and later on bio-accumulate in the food chain, thus causing detrimental damage to the soil, water supply, vegetation, animals and humans (e-Cycle, 2013). The effects on humans are wide as in that there is high possibility of damage to the reproductive, blood and nervous systems, with the mention of cancerous development as well. As such in order to ensure that the ever-increasing WEEE does not end up in landfill there is serious need for electronics recycling initiatives.

Another issue is that of the conflict materials. Over the past years, electronics companies have had a lot of pressure on them to ensure that their products are free as much as possible of conflict minerals especially those from the Democratic Republic of Congo (DRC). CDs being a consumer electronic have a high connection to the demand for the so-called conflict minerals from the DRC. Of the elements analyzed by Beverley et al., the typical conflict minerals are all present viz. tantalum, tin, gold and tungsten (Gosling and Prendergast, 2011).

### 1.7 Glues

Ease of disassembly has a direct impact on the commercial feasibility of repair and recycling, both are desirable from a sustainability viewpoint. The disassembly time drives cost that in case of recycling must be balanced against the revenue from the recovered materials and in case of repairs is one of the determining factors of the repair price and thus indirectly influences the end consumer acceptance for repairs. As Stobbe et al. (2017) have clearly stated, the use of gluing joints is a critical factor in the disassembly of smartphones. Even if the gluing joints can be separated by the application of heat, this adds to the time needed and complexity of a disassembly. It is becoming particularly bad if the gluing joints cannot even be separated by the application of heat. Although a better design for repair and recyclability for CDs is homework for the electronic industry and thus it needs to be done by itself, there is one thing the chemical industry can help with. As stated above, it is not likely to abolish gluing joints completely, but an expedient would be to devise innovative glues that facilitate disassembly. Potential ideas to achieve that will be discussed below.

## 2. Deutsche Telekom AG as an element of the supply chain

DTAG is heavily committed to the Sustainable Development Goals (SDGs) of the 2030 UN Agenda of Sustainable Development. As such corporate responsibility is an essential element of DTAG's business operations (see e.g. annual report (Deutsche Telekom, 2018)).

DTAG perceives itself as an important player in the SC. As shown above there is a clear need for the whole industry to introduce GSCM which is only possible by a close cooperation between the players in the SC. In pursuit of its corporate responsibility DTAG strives to intensify the cooperation in the SC to move towards GSCM.

CDs are heavily dependent on the network infrastructure. DTAG is at the interface and aims to have the CDs optimized for its network infrastructure to provide customers with the best possible network service experience. As part of that aspiration, DTAG issues technical specifications for CDs to ensure this best possible network experience. Since about 5 years requirements for sustainable design practices are part of that technical requirements set. The number of sustainability requirements as well as their ambition level has increased over the years. The intent is to guide the industry towards more implementation of sustainable design practices and thus to establish the ambitions for more GSCM with a tool.

## 3. Measures for more sustainability already taken by DTAG

Several researchers criticize harmful substances inside CDs, e.g., Cook and Jardim (2017), Dziamski (2014) and Stobbe et al.(2017). According to the opinion of the authors of this publication, although the existence of harmful substances in assembled CDs is by no means to be neglected, particularly plasticizers pose a problem as those may be released from polymer matrices, the key risk is in their uncontrolled release during mining, processing or component manufacture further up the SC. Likewise, the same risk may apply during recycling, particularly when not done professionally. Having so many mines, refineries, factories and workshops around the globe working with the associated minerals, components or complete CDs, it is practically impossible to control the risk at the root. Abstaining from harmful substance use in CDs has thus a multiplying effect as the environmental risks at each of the parties of the SC are also reduced as these numerous facilities do not need to process harmful substances then in the first place.

This is therefore an area requiring dedicated consideration and, foremost, action. In Europe, legislators have already taken action and have banned certain harmful substances from electrical and electronic devices. As already mentioned, the directives relevant for CDs is Reduction of Hazardous Substances (RoHS – 2011/65/EU), in Germany transposed into the Elektrostoff-Verordnung (ElektrostoffVO). RoHS limits polybrominated biphenyls (PBB), polybrominated diphenylethers (PBDE), lead (Pb), chromium of the oxidation state VI (Cr VI) and mercury (Hg) to 1000ppm in each component not further separable, while cadmium (Cd) is even limited to 100ppm. However, some selected exemptions to these limitations apply to cater for applications where there is not yet a substitute for these substances. For instance, 4 % Pb as a hardening element in copper alloys is exempted. This exemption is used in power plug pins to provide sufficient abrasion resistance for this application. Directive 2015/863 has added limitations for four phthalates (DEHP, BBP, DBP and DIBP) with a threshold of 1000ppm each, valid from July 22, 2019 onwards.

EN 62321 is the norm defining the chemical analytics to determine the essay of the substances limited by RoHS and to prove thus conformance to this directive. Various test labs offer chemical analysis following EN 62321 as a standard service. Each component is screened using X-ray fluorescence spectroscopy (XRF) followed by confirmation analysis by other methods if one of the elements limited by RoHS is found in the XRF spectra for certain components. Whenever DTAG is legally deemed the producer, an analysis report according to EN 62321 is required and formally approved by DTAG to ensure legal compliance.

In addition to RoHS also REACH (1907/2006) applies to CDs (European Commission, 2006). This is mainly related to Substances of Very High Concern (SVHCs). Chemical analysis reports for SVHCs are also evaluated for CDs where DTAG is legally deemed the producer. However, none of the SVHCs has been found in such CDs so far.

These directives are usually created in legislative procedures with the involvement of several stakeholders. In many cases this means a compromise in the sense of the least common denominator. Therefore, DTAG has commissioned a scientific study to investigate harmful substances typically found in CDs (Clemm and Deubzer, 2014). These harmful substances have been sorted according to whether already restricted by law and where a voluntary restriction would be desirable from an environmental viewpoint. Based on this, DTAG has put in 2015 into its technical requirements a voluntary limitation for phthalates, halogens, arsenic (As), antimony (Sb) and beryllium (Be). Phthalates have been limited by DTAG to 1000ppm in each non-separable component, where the whole substance class as such is limited. RoHS is following 5 years later, but only limits 4 phthalates out of a much larger number of this substance class still commonly in use. In relation to halogens DTAG follows the norm IEC 61249-2-21 for halogen-free: maximum 900ppm chlorine, maximum 900ppm bromine or 1500ppm of both halogens combined. This implicitly prevents the use of PVC or chlorinated respectively brominated flame retardants. As, Sb and Be have been limited to 100ppm each analogous to the limitation of Cd by RoHS. Only gallium arsenide has been excluded as there is presently no adequate substitution for this semiconductor material. Subsequent discussion with the SC has effectuated that several major players in the CD industry widely follow DTAG's voluntary substance limitations.

The analytical proof for the voluntary harmful substance limitations of DTAG is so designed as to be executed in synergy with the evidence for RoHS conformance in analogy to EN 62321.

Substances for CDs are not selected for the sake of itself. Besides cost and availability considerations, substances are chosen as a best material fit for a certain set of functional requirements. DTAG's voluntary substance limitations do not pose hardware designers with unsurmountable hardware design challenges. In a follow-on study Clemm et al. (2015) have been able to demonstrate that for each of the substances limited voluntarily by DTAG, substitutes are readily available on the market. This in turn demonstrates that at least in these cases substance selection for CDs has alternatives for substitutes. The challenge is rather to have some CD suppliers considering such alternatives, but in these cases, there are no unsurmountable physical obstacles.

DTAG also strives to foster circular economy as part of its sustainability policies. As such DTAG requires the use of post-consumer materials in devices and device packaging. While this works quite well with post-consumer cellulose fiber for packaging materials, the use of post-consumer plastics still has some challenges. Post-consumer plastics are shredded and added to a certain percentage to plastic pellets for the mold injection of new plastic parts. This has the disadvantage that the additives optimized for the previous use are dragged into the new application for which they are not intentionally designed. For instance, it is very difficult to obtain bright colors for plastic housings when using high percentages of post-consumer plastic. In consequence, DTAG's desire to use higher percentages of post-consumer plastics meets technical limitations and requires a compromise with other DTAG requirements. The chemical industry is seen here as the solution provider to solve this dilemma by developing innovative plastic waste processing procedures and novel materials that will not require such compromises. The authors of this publication see that as the prerequisite to request 100% post-consumer plastics from the CD industry. In the following sections we will look into trends and propose some development routes how this can be achieved.

## 4. Upcoming measures by DTAG

Legal and DTAG's voluntary harmful substance limitations, as described above, do not cover all harmful substances that may be present in or used for the manufacture of CDs. The UNECE globally harmonized system of classification and labelling of chemicals (GHS) defines in part 3 (H300-373) various health hazards and in part 4 (H400-433) various environmental hazards. The ideal from a sustainability viewpoint of course would be that none of the substances classified by any such hazard statements is used in or for CDs. DTAG has recently included this into its technical requirements.

Though DTAG is fully aware of the fact that this is quite a challenging requirement for base material developers, it is nonetheless intended to send a signal into the industry that sustainability needs to become a more significant target for base material development. Thus, in a realistic expectation, it will take some lead-time before this requirement will be completely fulfilled, but it is important that the conscious consideration of hazard statements of candidate constituents becomes a routine criterion for the formulation of materials. CD components must be developed and selected following a sustainability risk minimization principle.

Another route to approach the fulfillment of this requirement is to reduce the amount and variety of material components to the inevitable minimum as any additional component increases the risk of having a substance in with a relevant hazard statement. In addition, a large variety of components also renders material recovery as part of recycling more difficult, particularly if certain substances are present inside CDs in just very small amounts. For plastic materials, the at least theoretical ideal would be a composition of only the polymer without additives. The vision would be to modify the polymer structure itself to get the material properties as close as possible to the desired ones. Parameters could be the average chain length, degree of cross-linking or modifications to the monomer molecules. This changes the polymer synthesis strategy from large batches of the base polymer, which needs to be customized by additives, towards more, but smaller batches of individual polymers, which are already customized by their structure and contain smaller amounts of additives or none at all. This strategy would also have the advantage that the additives do not pose such a problem for applications using post-consumer material or in waste plastic processing. Reducing the material components diversity inside CDs thus serves two important sustainability targets: ease of recycling and harmful substance avoidance.

The challenges with the presently available post-consumer plastic have already been discussed above. Notwithstanding this, DTAG sticks to the requirement of using the highest percentage of post-consumer material that is technically still feasible, which is ideally 100%. DTAG sees a resolution in innovative processing procedures for waste plastic that allow to yield post-consumer plastic that is chemically identical with plastic obtained from fossil sources.

Potential ways to do that will be discussed in the next section.

## 5. Resulting requirements for more sustainable materials

### 5.1 Sustainability as a differentiator in a highly competitive industry

With the awareness that logistics and SC managers need to ensure the balance between cost reduction and innovation while at the same time maintaining good ecological performance, GSCM as such has become an important competitive approach for organizations, with multinational enterprises setting up global networks of suppliers to take advantage of country-industry specific characteristics for building on competitive requirements (Pagell and Krumwiede, 2004; Narasimhan and Carter, 1998). Although the benefits of GSCM and CLSC practices have seen increasing importance, there also exist the environmental regulations such as the EPR, WEEE Directives and RoHS, which have pushed the market's competitive standpoint towards a more sustainable one. Christmann and Taylor (2001) mention that sustainable SCM practices such as GSCM and closed supply chain loop (CLSC) have been implemented by Chinese enterprises as a means to establish foreign relationships and assure foreign market positioning. The analysis of their survey data showed that firms in China with multinational ownership, multinational customers, and exports to developed countries increase their self-regulation of environmental performance.

### 5.2 Concepts for a Circular Economy for technical polymers

One problem of the present polymer economics is the for polymers required carbon is still coming mostly from fossil sources. From a sustainability perspective, it would be desirable to circulate the carbon that is already in the atmosphere. As already mentioned, the main strategies presently to deal with waste polymers are landfilling, incineration or mechanical recycling. The key problem in case of mechanical recycling is the presence of residues from the first use during the second melting process (Hong and Chen, 2017). These authors deemed this approach therefore as a temporary solution. The authors of this study believe that the presence of residues from the first use or recycling process significantly limits the applicability as post-consumer material. This in turn leaves presently few alternatives to reuse waste polymers aside landfilling or incineration. Thus, in order to create demand for post-consumer plastic other recycling strategies need to be found that remove the limitations imposed by the presence of residues from the first use. Such a demand would be a promising strategy to remove substantial volumes of waste polymers from landfilling and incineration channels. Therefore, the following subsections discuss alternative strategies on how to improve the Circular Economy scope for plastics:

- Chemical decomposition of plastic waste to obtain monomers
- Plastic made from renewable sources which is also biodegradable (mimicking the seasonal leafage cycle)
- $CO_2$ as a reagent for the synthesis of polymers and common monomers

#### 5.2.1 Chemical decomposition of waste plastic to obtain monomers

The most abundant technical polymers used in CDs are polycarbonates (PC), acrylonitrile-butadiene-styrene copolymer (ABS) or a blend of both. Typically, housing and structural parts consist of these polymers which are thus by weight the most significant polymers used in CDs. Other uses of polymers are the carrier materials of printed circuit boards, which in most cases consist of glass-reinforced resins, and displays where in some cases polymethylmethacrylate (PMMA) substitutes PC as the material for transparent foils. There are other plastic parts, such as connectors and flexible cables to connect components inside CDs, but which are in terms of the contribution to the total polymer weight just minor.

To ensure that the recycling of these polymers is sustainable it is necessary to have a circular economy approach. Of the various solutions being researched, chemical recycling seems to be the one with the most progress concerning the environmental and technical benefits (Hong and Chen, 2017). With regards to PC, they have high valuation as they belong to a class of engineering plastics which exhibit excellent mechanical and/or thermal properties, with a global market compound growth rate of 8.2% expected to reach $91.8 billion by 2020 from $57.2 billion in 2014 (Smith, 2019). Sad enough the unique resin structure means that PCs cannot be mechanically recycled and end up mostly in landfills as waste (Antonakou and Achilias, 2013). To remedy this situation, Jones et al. (2016)mention that waste PCs can be repurposed into value-added poly(aryl ether sulfone) known as PSU materials, which as a type of technical polymer can be used for reverse osmosis and water purification membranes, as well as high-temperature applications (Jones et al., 2016). It is mentioned in the same study that PC is chemically decomposed under influence of an alkali with $CO_2$ being lost as a by-product, and the product bisphenolate then in the presence of a carbonate salt undergoes a polycondensation reaction at 190 °C for 18h to produce the PSU. This method as such ensures a PC cradle-to-cradle life cycle.

On the other hand, the PMMA through pyrolysis at temperatures of 450 °C can be effectively depolymerized to more than 98% of the monomer (Kaminsky et al., 2004). Nevertheless, the existence of colorants and other contaminants might lead to the production of non-wanted/ environmentally dangerous by-products. Another solution to the issue of recycling for both ABS and PC is that of combining both scraps (Larsson and Bertilsson, 1995). An ABS or ABS/ PC blend enables certain mechanical properties to be recovered, especially toughness lost during usage either artificially or naturally. However, this works only as second-life solution seeing as the gotten product will need recycling in the end. A means to remedy these issues is the use of bio-based polymers as discussed below.

### 5.2.2 Bio-based polymers as sustainable substitutes

Nature has already established a circular economy for leafage. In autumn trees and bushes drop their leafage which in turn is decomposed by microorganisms to $CO_2$ and water. In spring, the whole process is turned around and leafage is generated by photosynthesis from $CO_2$ and water. In analogy to that, the circular economy for polymers can be closed by the synthesis of polymers from renewable sources (i. e., plant material) and by also making those polymers biodegradable. To avoid potential ethical conflicts, only those renewable sources may be used that are not in competition with foodstuff.

Agarwal et al. (2012) analyze in their 2012 study the plant-based monomer $\alpha$–methylene-$\gamma$–butyrolactone (MBL) or tulipalin A (Agarwal et al., 2012), they state that bio-based polymers can be made from monomers that are either bio-based (derived from renewable sources) or naturally gotten from plants. The monomers can be polymerized through various techniques like condensation polymerization, vinyl polymerization, ring-opening polymerization and metathesis polymerization with the use of renewable sources such as plant oils, polysaccharides and sugars. There is also the possibility to directly produced vinyl polymers from plant-based monomers. One of these is MBL, which as an alternative to petroleum-based methyl methacrylate (MMA), can be found naturally in tulips or produced from biomass feedstocks. It can be used as a natural gotten vinyl monomer for the synthesis of biopolymers, due to its exo-methylene double bond.

### 5.2.3 $CO_2$ as a reagent for the synthesis of polymers and common monomers

Although $CO_2$ is an inert molecule it still can be converted with energy input and suitable catalysts into polymers, monomers or monomer precursors. There are numerous publications dealing with the subject. Here only a brief selection is discussed which has a potential relation to the circular economy for polymers.

Out of those only one is cited here to illustrate the principle: Wasmus et al. (1990) have investigated the electroreduction of CO2 at copper electrodes. Methane and ethene have been found as reaction products. The authors have been able to identify conditions where more ethene than methane is produced. Ethene in turn is used directly as a monomer or precursor of monomers in various synthesis routes for polymers.

These electrochemical approaches will show their full potential for sustainability when the required electrical energy is generated from renewable sources, such as photovoltaic or wind energy.

Another alternative to input the energy required to reduce $CO_2$ is the utilization of light in photochemical approaches. One of them is the photo-catalytic conversion of $CO_2$ to hydrocarbons and renewable fuels such as methane and ethylene (Steinlechner and Junge, 2018; Royer et al., 2018). Ethylene in its oxide form can be readily used as raw material alongside $CO_2$ and bisphenol for PC production in a phosgene-free process (Fukuoka et al., 2003). The direct use of light energy enables the usage of intermediary energy to be avoided as in potential electrochemical approaches.

Both approaches are still in the state of fundamental research, but show the basic feasibility of this strategy for the Circular Economy of polymers. Before becoming suitable for technical application, various problems need to be overcome, such as low conversion efficiency, high overvoltage in case of electrochemical approaches and long-term catalyst stability. Therefore, this is certainly not a short- or even mid-term solution but deserves further research as a long-term enhancement of the options to establish a circular economy for polymers.

There are also approaches to use $CO_2$ directly for polymer synthesis. For instance, there are already technical processes for the synthesis of PC through copolymerization of $CO_2$ with epoxides (Klaus et al., 2011). This idea has been around for more than 40 years now, first provided by Inoue et al. who through this copolymerization with a heterogeneous catalyst produced from diethyl zinc and equivalent water, opened up the a new filed to $CO_2$-based polymers (Inoue et al., 1969). Following this, a team again composed of Inoue in 1983 combined ZnET2, water, $CO_2$ and PO to produce a small quantity of polymeric material in the first single -site catalyst process for $CO_2$/epoxide copolymerization (Aida and Inoue, 1983). Lu et al. (2012) analyzed the development of highly Co (III)-based catalysts for the PC selective production from alternating copolymerization of $CO_2$ epoxides. Reason for this as stated in their research is that, although this method of $CO_2$ usage could yield a very valuable polymeric material – biodegradable PC, it often generates unwanted by-products such as polyether and ether linkages, which disperse within the PC chains. Because of this, the catalyst choice is seen as critical factor for the selective creation of the expected product. This selective transformation of $CO_2$ into biodegradable PCs as such sets the stage for potential large-scale sustainable utilization of $CO_2$ in chemical synthesis.

### 5.3 Reducing harmful substances and substance diversity in communication devices

The substance diversity in CDs has mainly two consequences for sustainability:

- The risk that one or more of these substances have harmful properties grows with their number.
- Material recovery during recycling is impeded.

Consequently, reducing harmful substances and substance diversity in CDs shows a congruency to some extent. After having reduced substances to an inevitable minimum, the residual task is to ensure that the remaining essential substances are selected in a way as to have no harmful properties or, at least, their harmfulness corresponds to the absolute minimum that is technically feasible.

There is also a commercial risk in so far as some of the materials are scarce and may get into short supply which drives cost. This is particularly valid for those substances whose natural mineral deposits are concentrated in a few countries or even just one. Any political problem in or with those countries may have an immediate impact on availability.

These constitute good reasons to devise strategies to reduce the substance diversity in CDs. Based on recent requirements from DTAG, strategies to reduce substance diversity in polymers have already been discussed above. The question is which strategies may apply for the other components that go into CDs. For metals it seems straightforward: copper is probably irreplaceable due to its good electronic conductivity. For the other metal parts, the authors can very well envision a unitary metal or alloy that combines the required physical properties of the various parts in an at least reasonable compromise. This would have significant benefits for sustainability:

- The number of mines in the SC and their potential negative impact would be reduced, as there are a fewer minerals required as the starting points of the SC.
- Sorting during recycling would be reduced as there are only two different types of metal (copper and the unitary metal).

- Material recovery would be facilitated as having a unitary metal means that its amount per CD is typically larger as if the metal portion of a CD is shared by several metals.

Sorting batteries from recycled CDs is already relatively straightforward as there is across CDs a de facto unitary solution in the form of Li-ion batteries with only a few exceptions.

Reducing the substance diversity in electrical parts, such as ICs, resistors, sensors and capacitors, is comparatively more complex. Even the same kind of electrical part may have sub-types which all are distinguished by their chemical composition. In a first step it would be desirable to reduce the number of different sub-types for each electrical component inside CDs which would eliminate already some of the substance diversity. In another step it would be desirable to develop a multi-purpose material that is good enough to be used across a range of electronic components by having properties broad enough to fit the different physical and chemical requirements of the application in different electrical parts. By way of example electrolytic capacitors are available made from oxides of aluminum, niobium or tantalum. For the authors it seems to be feasible to agree for that purpose on one of the materials and abolish the other two, or for that matter, develop a “super”-material that is able to replace all three of those.

### 5.4 What can the chemical industry do to make CDs more repair and recycling friendly

As was discussed above the frequent use of gluing joints in CDs is hampering repair and recycling. The key to this problem is the requirement that the glue needs to keep parts firmly fixed during use. That benefit turns into the opposite when a low connection force is desired, that is disassembly for repair or recycling. This dilemma could be resolved by designing a glue that fulfils both: It will hold the parts firmly during use but stops doing so when required. This concept requires a type of adhesion that can be annulled by any form of a suitable trigger. This implies some form of control of the molecular forces at the interface between glue and bonded part by a suitable physical or chemical mechanism. The authors are aware that this is quite a challenging development task, which probably even requires some better fundamental understanding of molecular forces at the interface.

## 6. Conclusion: suggested strategies for more sustainable materials

There are political, social and economic drivers for more sustainability expected to become more significant in the foreseeable future. Parallel to that, sustainability will gain a growing impact on corporate operating costs by GHG taxes, emission certificate trade or other means. The CD industry will need to find an answer to that.

Base materials play an important role for CDs. Although there are several promising approaches in the industry, the authors see a differentiation and growth potential for base materials that help the CD industry to become more sustainable. This in turn requires some redirection of product development strategies in the chemical industry as the supplier of base materials for the CD industry. Differentiation by innovation and sustainability can be merged.

Innovation is not only about inventing new products; likewise, existing products can be done in innovative processes that reduce the GHG emissions and other environmental impacts during their production. The differentiation is then by helping the following parties in the SC to also reduce their footprint. Even higher prices may still be accommodated by being balanced against lower taxes or costs for GHG emissions certificates. Novel procedures for waste plastic processing for better material reuse, innovative polymer formulations to reduce additives and harmful ingredients or the use of biopolymers, all have the potential to become such differentiating products for the chemical industry.

“Super”-materials that can be used in several functions in electronic components, that today require the use of several different ones, could be another strategic development approach to leverage the smartness of the materials also into more sustainability. Even though demanding, intelligent glues, that stick when they should, but do not stick when they should not may be also a strategic development approach. Not only in the CD industry have gluing joints played an increasingly important role, but also in other industries.

All those approaches still require additional development efforts in labs, in pilot plants and large-scale manufacturing. This is a chance for those industrial sites that have the infrastructure and experience to cope with it. In fulfilment of its own responsibility, DTAG sees its role in mediating between the different players in the SC and thus bringing sustainability into CDs. At the end, sustainability is a team effort in the SC.

As a limitation, this study lacks a sufficient data framework for sampling and this means that certain measures especially concerning recyclability are missing. As a proposition for further works and to ensure that an in-depth analysis can be conducted, more information relevant to CE for CDs such as ecological carbon footprint data and fair labor needs to be gotten.

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