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Quality of resources: a typology for supporting transitions towards resource efficiency using the single-use plastic bottle as an example

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Abstract

The growing British waste management sector has consistently voiced the need to improve the quality of waste-streams and thus the value of secondary resources produced, in order to achieve higher reprocessing rates. Mismanagement of wastes that may lead to contamination and degradation of the recyclate feedstock constitutes one of the main barriers in the pathway to a circular economy. The sector has also repeatedly called upon manufacturers to collaborate in designing materials, components and products (MCPs) with properties that aid recovery, refurbishing, repair and recycling (e.g. separabilty of materials, clear labelling), as waste managers recognise the value of early engagement well before MCPs enter the supply chain (i.e. before MCPs are produced and distributed to the end user). Nonetheless, progress has been slow with regard to improved design for promoting components and products longevity and segregation at source when they reach their end of use or life stage in order to promote circularity. China's ban on imports of low quality recyclates at the end of 2017 marked the beginning of a new era in waste management, drawing attention to UK's dependence on export of low-value secondary resources and thus placing 'quality' in the spotlight. This article delves into the notion of quality, the way it is understood and assessed at different parts of the MCPs lifecycle, and makes recommendations on how it might be systematically measured. A typology to distinguish avoidable and unavoidable designed and created characteristics at all stages of MCPs lifecycle is proposed to provide industry with a tool to design wastes out of the economy. The typology's application is demonstrated using the single-use plastic bottles as an example.

Keywords: materials, components and products characteristics; waste management; circular economy; single-use plastic bottles; sustainability; interventions; multi-dimensional value

1. Introduction

Quality of wastes and secondary materials is perceived to be one of the main barriers to the greater recovery of resources from waste, including municipal solid waste, construction and demolition, and commercial and industrial wastes. Yet, quality remains an elusive notion. Traditional definitions such as "the standard of something as measured against other things of a similar kind; the degree of *excellence of something"* or *"a distinctive attribute or ch*aracteristic possessed by something" (Oxford Dictionary of English (3 ed.)) do not reflect that in reality, the quality of materials, components, and products (MCPs) produced, and those recovered from wastes, is defined differently by each stakeholder in the system. This is driven by a number of factors: the intended use of MCPs, which depends on the properties/characteristics and original purpose (for a designer/manufacturer); existing regulations/specifications (for a specifier); cultural mind-sets and attitudes towards resources recovered from wastes such as resistance to repairing, remanufacturing, reuse, recovery and recycling (for recyclers, reprocessors and manufacturers, but also end-users); and marketability and aesthetic aspects (for manufacturers, retailers, end-users and clients).

Quality measurements vary across different sectors and MCPs. These are often imposed by existing regulations, legislation and standards, other quality assurance and testing protocols, or are arbitrarily defined based on a combination of stakeholder expectations regarding what properties quality should reflect. Quality in the latter category is often determined qualitatively "on-sight", for example based on the visual appearance of MCPs (upstream the supply chain), or by interpreting the way different MCPs are separated at source (downstream). Large amounts of fruits and vegetables that are not the 'right' shape or size are thrown away because retailers do not consider these to be up to the 'high-quality' standard demanded by consumers, leading to perfectly edible food being wasted (The Guardian, 2013); large amounts of non-target (often unrecyclable) MCPs being placed in the wrong recycling receptacles can cause entire loads of recyclable MCPs to be rejected because the overall quality might be compromised due to contamination (edie.NET, 2016). Rejection of this type can also occur at material recovery facilities (MRFs); but when materials such as paper, glass, metals and plastics are eventually sorted for further processing the quality definition changes. For example, plastic recyclate quality is often categorised by colour (e.g. translucent and clear plastics are considered of better quality) or by type (e.g. polyethylene terephthalate (PET) and high-density polyethylene (HDPE) are considered to be high-value streams and thus, are always targeted for sorting); other plastic materials may only be considered as contaminants even though it may be technically possible for them to be recycled.

Quality measurements for MCPs, especially in Europe, are based on specific regulations, specifications and testing protocols. For example, the production of packaging intended to come in contact with food and drink (known as food contact materials, FCMs) needs to comply with the EU food contact legislation (Regulation (EC) No 1935/2004; Regulation (EU) No 10/2011 for plastics); whereas textiles production must be aligned with the EU Textile Regulation (EU) No 1007/2011 on fibre names and related labelling and marking of the fibre composition of textile products. Some quality measurements for MCPs recovered from waste follow the same principle, with various regulations, quality protocols and standards supporting their use up to the necessary levels of environmental and human health protection, safety and hygiene. In the case of solid recovered fuel (SRF), a product derived from waste, quality is measured and regulated via a set of technical criteria outlined in the EN 15359 standard with the (i) the net calorific value (NCV) (also known as lower heating value), (ii) the total chlorine (Cl) content, and (iii) the mercury (Hg) content, being the most critical based on the end use (Iacovidou et al., 2017a). Another product derived from waste is compost, of which quality is measured via a range of physical and chemical indicators including solids (e.g. glass and non-biodegradable fragments), heavy metals (e.g. Cd, Cr, Cu, Pb, Ni and Zn), humic substances, pH and other organic contaminants (e.g. polycyclic aromatic hydrocarbons (PAHs), polychlorinated dibenzo-p-dioxins/polychlorinated dibenzofurans (PCDD/Fs)), the concentrations of which are outlined in the Compost Quality Protocol and PAS100 (developed as a requirements of end-of-waste criteria set in the Waste Framework Directive 08) as well as those that can be used in different applications (Farrell and Jones, 2009). For recyclable materials such as plastic, quality at the reprocessing stage is measured by following a testing protocol that measures additives concentration, viscosity and moisture content, amongst others. Variations in quality measurements may create complexity and/or uncertainty in the system as a result of variations in the way regulations, standards and/or protocols are applied to different places. However, their purpose is to ensure that the MCPs recovered from waste meet the MCP specifications required at the production/application level in which they are going to be used; assuring high-level performance and public safety.

Based on the above, we concluded that if quality is to be measured according to the suitability of the MCPs to continue to be used for the same function or an alternative use, a better definition is needed. Therefore, quality of MCPs is defined here as: the remaining functionality described via the inherent, designed and created characteristics of a recovered MCP that make it suitable for the same or a different application measured against the properties required for assuring good performance and public safety in the specific application. Based on this definition, the quality of MCPs can be determined and affected by actions at any point in their lifecycle, from their initial design through to their disposal and end-of-life (EoL) management (Hahladakis and Iacovidou, 2018). The objectives of this article are: 1) to provide a description of how each step of the MCPs lifecycle might affect their quality and generate insights into the key attributes that must be taken into account when assessing interventions made upstream or downstream of the point where wastes are generated, as shown in Figure 1, aimed at improving the quality of MCPs recovered from waste (Iacovidou et al., 2017c) (Section 2); 2) to propose a typology for assessing the type of improvements that could potentially be made for increasing the quality of MCPs recovered from waste (Section 3); and 3) provide a simple illustrative example of how the typology developed could be used (Section 4). The final section of the article concludes with recommendations for furthering this research.

Figure 1 The point where materials, components and products (MCPs) are discarded as wastes marks the transition from the upstream to the downstream part of the system. Reuse, remanufacture, and secondary material produced via recycling processes are key stages in closing the loop between downstream and upstream parts of the system.

2. Impact of all stages of materials, components and products (MCPs) lifecycle on their quality

The composition of MCPs is defined here as the complex suite of interacting inherent and designed characteristics (e.g. colour, density, hardness, electrical conductivity, corrosion/oxidation resistance). The inherent characteristics of MCPs are those that either:

- occur naturally (e.g. those of wood, raw foodstuffs, metallic elements, dimensional stone, cotton, gemstones or crude oil); or
- are produced by chemical, thermal and mechanical processes that offer a particular combination of technical properties (corrosion resistance, mechanical properties and service life) relevant to a particular use, and which cannot be changed (e.g. those of polymers, processed foodstuffs, engineered composites or metal alloys); called herein as ‘chemically produced’ characteristics.

The designed characteristics are those that occur during the fabrication and/or amalgamation of different materials to elicit a particular appearance and ‘feel’ (e.g. colour in plastics and paper, seasoning in foodstuff, aroma in personal care products, coating in glass and ceramic components, surface finishes in cars), as well as to enhance MCPs performance and reliability (e.g. preservatives in foodstuffs, additives in polymers, paint coating in steel components, multi-layered crisp bags and pill packets) and function (e.g. design for disassembly, ability to be repaired and serviced) (Garvin, 1987). Designed characteristics supplement inherent features and are intrinsic to the final MCPs that reach the end user.

Understanding composition is critical in assessing the performance and EoL management of MCPs. For instance the aluminium-lithium (Al-Li) and aluminium-magnesium-lithium (Al-Mg-Li) alloys used in aircraft metal production, although separated from other components and materials, cannot be recycled using normal facilities. This is because lithium creates an explosion hazard in the aluminium remelting phase; a consequence of 'chemically produced' inherent properties (Suomalainen et al., 2017). However, the extra technical value imparted by the aluminium-lithium alloys, such as low density, high elastic modulus, high strength and superior fatigue crack growth resistance, is currently an efficient way of reducing material weight and improving longevity, potentially outweighing the environmental cost of preventing recyclability (Wanhill, 1994). In the anaerobic digestion of agricultural wastes, feedstocks with a high degradability, such as cereal grains, poultry and pig manures give a higher ammonium to total nitrogen ratio than feedstocks of low biodegradability (e.g. cattle manure and silage maize), leading to varying qualities of digestate produced that is used as a fertiliser; a result of 'naturally occurring' inherent characteristics (Möller and Müller, 2012). Biomass residues used as co-fuels in coal power plants contribute to an increase in the chlorine content of pulverised fly ash rendering it unsuitable for use as cement replacement in the concrete production industry; another example as a result of inherent characteristics (Iacovidou et al., 2017a).

In current practice, MCP manufacturers often bear little or no direct responsibility for the fate of the materials and components they use and products they make once they have left the factory gates. As such, MCPs are usually designed to prioritise efficiency of manufacture, consumer demands, attractiveness and competition against rival MCPs, but also use and ease of distribution over ease of recyclability. Common practices, such as the use of mixed materials (e.g. in crisp bags, coffee cups, juice boxes) make it very difficult for them to be separated and recovered at their EoL stage; hence the quality of these mixed materials is severely diminished by actions upstream (i.e. the manufacturing/application process) in the system. At the same time MCPs manufacturers are reluctant to repair products, use recovered components and/or recycled materials, ostensibly because of their perceived lower quality as opposed to new materials and components; additionally because it might impinge on the typical business models dependent on the sale of new, replacement products.

Traditionally in the UK, the quality of MCPs recovered from waste has been perceived as inferior, described in terms such as ‘dirty’ and ‘contaminated’ (Wrap, 2012). This is largely attributed to the practices followed downstream in the system, with disposal, collection and management practices affecting the quality of MCPs due to contamination of separately collected waste streams (e.g. recyclates) with other types of waste (e.g. food, textiles or even different types of the same material). Contamination is critical in determining the quality and fate of MCPs at their EoL stage. Some designed characteristics of MCPs can also be manifested as contamination during their EoL management (defined here as chemically induced contamination). For example, additives (e.g. antioxidants, stabilisers, plasticisers, and flame retardants) used to improve the performance of plastic products may be carried over to the new products made out of the recycled plastic; a designed feature that leads to contamination (Hahladakis et al., 2018); whereas the presence of plastic-coated food packaging, cartons, carrier bags and other items that are not certified ‘compostable’ in the biodegradable waste stream, can contaminate the compost produced; an externally induced contamination (Stangenberg et al., 2004; Vilaplana and Karlsson, 2008). Contamination of separately collected waste streams such as organics, paper, glass, plastics with other recyclable or non-recyclable materials is the most profound cause of physical contamination. For example, paper contaminated with glass fragments and/or is heavily soiled with organic material, might lead to machinery breakdowns, and/or the contamination of the entire batch respectively, leading to its diversion to incineration facilities or even landfill.

Another fundamental quality factor for consideration when assessing MCPs remaining functionality and recovery possibilities, is degradation, i.e. chemical and morphological alterations that change the mechanical and rheological properties (e.g. for polymers, chain conformation, molecular weight distribution, crystallinity, chain flexibility, cross-linking and branching) (Venkatachalam et al., 2012). Degradation occurs mainly during the use phase of MCPs as a result of their interaction with the environment and/or remedial measures taken to prolong lifetime and remediate damage. During the use phase, the characteristics and properties of MCPs may deteriorate due to exposure to environmental conditions (e.g. corrosion, oxidation, photo-degradation, biodegradation), and cumulative damage caused by physical loading, i.e. stress/strain, impact, abrasion and resultant deformation. For example, high moisture environments can cause wood to lose its strength and stiffness, corrode metals, and cause mould to grow on plastics – an environmentally (physically) induced degradation. Physically-induced changes may introduce structural heterogeneities in the MCPs, reducing their long-term stability and performance.

However, degradation during the handling/sorting stages may also be quite possible due to the technologies used, causing chemically induced changes that deteriorate the properties of MCPs during their collection, sorting and reprocessing. For instance, plastic materials exposed to thermo-mechanical degradation during processing may undergo internal chemical reactions caused by high shear forces and high temperatures in an oxygen-deficient atmosphere, which may affect the mechanical properties and stability of the recycled material (Hahladakis and Iacovidou, 2018; Vilaplana and Karlsson, 2008). This may lead to the production of lower quality resources suitable only for lower value products (cascading) – a chemically induced degradation.

Assessing factors such as contamination, degradation, and mixing of different materials can provide insights into the likelihood and scale of MCPs to retain good quality at EoL, and the way this may vary based on the use (e.g. exposure to environmental conditions, degradation state, and intensity of use), recovery (e.g. deconstruction, disassembly, collection method, presence of impurities), reprocessing methods and their technological advancement, the existing regulatory standards, and the logistic challenges associated with MCPs EoL management. For example, in the UK, glass contamination of the paper stream in material recovery facilities (MRFs) is considered to be a significant business risk for small and medium-scale plants where sorting technology is not advanced, whereas for bigger, more sophisticated plants this is not seen as an issue. Fifty different metals are used to produce a smartphone, only a small amount of which are presently recovered and recycled (Benton and Hazell, 2014); bricks bound together with cement-based mortar are difficult to recycle (Iacovidou and Purnell, 2016). The new generation of Near Infrared (NIR) detection technologies enables better sorting of plastic waste, ensuring that the plastic offered for reprocessing is correctly separated and that physical contamination is reduced. Plastic bottles such as those used to contain beverages, although theoretically reusable, have a threshold (which varies based on type of plastic) up to which they can be safely reused before they start leaking chemical substances such as DEHP and BPA into the liquid they hold, posing serious health hazards exacerbated by the intensity of their use.

3. Improving the quality of MCPs recovered from waste: a typology

It is interesting to note that while the inherent characteristics of materials are fixed and changes can only be inflicted by selecting different materials that have different inherent characteristics better suited to support their recovery at their EoL stage, the designed characteristics of MCPs, and those ‘created’ via the application, use, disposal and management practices (often closely linked to designed characteristics and technological methods used) are most likely to affect MCPs quality, and therefore the way these are managed at their EoL stage. Although in this article we focused specifically on contamination and degradation of MCPs, other factors may also give rise to created features that may impede MCPs recovery, reuse and recycling.

From our rather limited list of impeding factors and based on the designed attributes of MCPs, it can be suggested that changes in the quality of MCPs recovered from waste can in some cases be avoidable (e.g. contamination of construction components with asbestos or glass commingled collection with other recyclables) or unavoidable (e.g. contamination of recycled plastic materials by their additives). The notion of “unavoidable” waste has gained policy momentum in the UK over the past years, with government aiming for zero avoidable waste by 2050 (Velenturf et al., 2018). But what exactly is avoidable waste? The distinction between avoidable and unavoidable necessitates an understanding of the characteristics required for a specific function, and those intended for serving a purpose that goes beyond the functionality of MCPs, such as marketability, brand image or even businesses and individual values, agendas, needs and preferences. Quality in the latter case can be subjective because it involves perspectives on quality that come from the people involved at the various stages of the system (e.g. manufacturers, consumers and reprocessors alike).

Focusing strictly on an objective way of measuring quality that is based on the properties, characteristics and functionality of MCPs, we made the assumption that inherent characteristics are unavoidable; hence the distinction between avoidable and unavoidable characteristics is mostly associated with the designed and created features of MCPs. As shown in Table 1 it can be suggested that designed characteristics can be: i) necessary and unavoidable, ii) necessary but avoidable, and iii) unnecessary and avoidable; whereas created characteristics can be i) physically induced and unavoidable, ii) physically induced but avoidable, iv) chemically induced and unavoidable, and iv) chemically induced but avoidable.

The distinction between necessary and unnecessary designed characteristics may appear subjective. Designed characteristics can often be intentional due to marketability, attractiveness to MCPs, customer satisfaction and acceptability, and brand image (Garvin, 1987), but some are mandatory for the manufacture of MCPs that serve a specific function (e.g. crisp bags, coffee cups), or enhance MCPs properties and promote their quality preservation for longer. Designed characteristics in the latter category focus on the nature of MCPs and ways to prolong their life and as such are an objective measure of quality, whilst the other characteristics focus mostly on secondary factors (e.g. price, brand image, marketability and cultural values) which are critical for other purposes (Garvin, 1987), but unnecessary when it comes to promoting the longevity of MCPs.

Similarly, the created characteristics refer to the wear and tear of MCPs during their use and EoL management as a result of their exposure to uncontrolled environmental conditions (e.g. temperature, UV radiation, wind, acidification, etc.), and changes in their characteristics during their handling processes. These characteristics are dynamic in nature, and are often dependent on the repair and maintenance activities, the technologies used, the experiences and specific processes put in place in different contexts for the management of MCPs; thus the distinction between avoidable and unavoidable.

Table 1 Distinction between avoidable and unavoidable designed and created MCPs characteristics and their type. Designed attributes are classed into necessary and unnecessary; created attributes are classed into physically and chemically induced

Based on the above clarifications, a useful typology of quality properties to support changes in the way MCPs are designed, used and managed during their entire lifecycle, can be developed. This typology distinguishes MCPs quality into three dimensions:

1. Compositional - refers to the inherent characteristics, physical and those produced by the chemical, thermal and mechanical processes (referred here as chemically produced) that offer a particular combination of technical properties relevant to a particular use that cannot be changed;
2. Contextual – refers to the designed characteristics required for mixing different materials to create the properties relevant to a particular use and to enhance MPCs performance and reliability, as well as additional attributes that make it attractive, acceptable, marketable, etc.;
3. Dynamic – refers to the created characteristics based on area-specific environmental conditions and practices, cultural patterns, geo-political and economic situation and education.

Figure 1 illustrates the way this typology works. The distinction between avoidable and unavoidable characteristics is important for sustainable interventions in component and product design to be made, and/or the management thereof. The use of this typology must be mostly based on an objective quality assessment that focuses on properties and functionality of MCPs during their lifecycle. Whilst in reality this can be challenging due to the subjective way quality is understood at various stages in the system, it is a critical and necessary step in raising awareness; awareness that is not focused on the intended and desired elements of quality that serve purposes that go beyond the functionality of MCPs, but is instead focused on the conditions required for promoting changes and interventions to ensure the lifecycle quality and circularity of MCPs, and ways to implement them.

Figure 2 Typology of quality properties of materials, components and products (MCPs), based on compositional, contextual and dynamic quality dimensions as described in Section 2.

The typology presented in Figure 2 can only be used as a way of gauging potential interventions in the system for promoting enhancement and preservation of MCPs quality. It can be a preliminary step towards producing a framework that enables practitioners to gain an in-depth understanding of the properties of materials, their mixes, and additives used to improve their performance and the implications of these during their lifecycle, based on a whole systems perspective. Findings from this step must be combined with the manufacturing industry's needs to develop MCPs that are marketable, acceptable and attractive to consumer within limits that allow for multi-dimensional value-based decisions to be made. Only then decision-makers can identify feasible and viable changes and interventions required for supporting the prevention, reuse and recycling of MCPs.

It might be the case that action is needed at one or various stages of the value chain in order to enable such changes to promote the longevity and/or circularity of MCPs in the economy, whilst providing safety, performance, comfort and aesthetic value to the end-users (Hahladakis and Iacovidou, 2018). It is important however, for any identified changes to be subjected to a multi-dimensional assessment and valuation process to uncover potentially hidden implications of these adaptations in both space (e.g. regional, national, global scale) and time (e.g. short-, medium- and long-term) (Iacovidou et al., 2017b; Millward-Hopkins et al., 2018).

4. Application of the typology using the single-use plastic bottle example

Plastic bottles made from polyethylene terephthalate (PET) are highly engineered materials made from petrochemicals (chemically produced) that possess a number of unique properties that enable them to perform well as a beverage packaging. PET bottles are often designed for single use only, which means that they are discarded soon after their use. Once they become waste they go through collection and management, with recycling being the optimal value recovery process. Across these stages PET bottle's quality is degraded often to such an extent that closed-, or even open-loop recycling (for definitions look at (Iacovidou et al., 2017c)) is not possible; hindering its looping back into the economy. Using the typology developed herein, we scrutinise how PET bottle's specific characteristics affect its potential circularity.

The inherent properties of PET bottle, shown in Figure 3, are those attributed to the high molecular weight polymeric structure (e.g. mechanical strength, toughness, resistance and flexibility) (Al-Sabagh et al., 2016) and are considered to be unavoidable. As a result, our quest to understanding how PET bottles quality degrades across its lifecycle, depends on gaining an insight into how the designed and created characteristics shown in Figure 3, can affect its recyclability. This is by no means an exhaustive list of designed and created characteristics, but it gives an indication of some common issues associated with PET single-use bottles quality and recyclability.

Figure 3 Use of the quality properties typology to uncover potential interventions that can be made for improving the quality of recovered PET bottles.

Beginning from the designed characteristics, our approach to understanding avoidable and unavoidable characteristics is based on the current advances and technologies available in designing single-use PET bottles. Nowadays, PET bottles come at various shapes and sizes and are made of thin walls that make them more than 30% lighter than 15 years ago (BPF, 2018; Deligio, 2009). The stretch blow molding process (F. et al., 2004) employed for the manufacturing of PET bottles has been advanced at such level that promotes the production of thin walls with a molecular orientation and crystallisation level, which give the bottle the desired mechanical, optical and barrier properties (Subramanian, 2000); an unavoidable characteristic (Fig. 3). Despite the belief that PET bottles are made entirely from PET, bottles are often composed of a polypropylene (PP) cap and a label made from polyvinyl chloride (PVC); two different types of plastics. These components have the potential to contaminate PET bottles during recycling, and as such their removal is considered to be critical.

Contamination is considered to be the major cause of deterioration of PET's physical and chemical properties during reprocessing, and hence of its recyclability potential (Al-Sabagh et al., 2016; Awaja and Pavel, 2005; Giorgio et al., 1994). The PP and PVC components need to be removed and although sorting processes are beneficial in removing a significant fraction of these, some may still remain creating problems during the reprocessing stage. Replacing the PP cap with a cap that is made of PET to decrease the risk of contamination is a characteristic that is currently not considered to be avoidable. This is based on the premise that PP cap provides a tighter seal, whilst investment in technologies that are currently used to get this separated from the bottle in the sorting systems creates a perverse incentive to not promote any changes. This prevents new designs for substituting PP caps with PET to be developed, however, closure systems that contain no liners and leave no residual rings are promoted for ensuring easier removal and lower risk of contamination (APR, 2012; WRAP, 2009).

The presence of PVC, even as little as 100 ppm, in the PET reprocessing stage can lead to the generation of hydrochloric acid, which acts as a catalyst for the chain scission reactions during the melt phase and discolours the recycled PET during processing (Awaja and Pavel, 2005). Therefore, the use of PVC labels should be avoided and new labelling systems are increasingly being promoted; slowly phasing out PVC labels which is evidently considered to be an avoidable characteristic. For example new sleeve labels and coloured coatings with removable inks have been trialled in the UK and have shown to be successfully removed during PET bottles reprocessing (WRAP, 2010).

The adhesives and additives used in the manufacturing of single-use PET bottles (e.g. plasticisers, colour coatings, oxygen scavengers and ultraviolet light absorbers) (Chilton et al., 2010). Adhesives can for example prevent the separation of labels from the PET bottles during the washing stage (APR, unknown; WRAP, 2010). Additives can cause undesirable effects during reprocessing (e.g.

discolouration, degradation and pollutants release) (APR, 2012; Hahladakis et al., 2018), affecting as such the successful sorting and reprocessing of bottles into secondary raw material of good quality characteristics (Awaja and Pavel, 2005; Subramanian, 2000). Similarly, the use of degradable additives can shorten the useful life of the bottles and therefore affect their ability to be recycled (APR, 2012). The impact of degradable additives in the reprocessing stage of PET bottles is currently unclear and therefore should be avoided. With increasing awareness on the need for promoting recyclability, the use of alternative additives are being promoted. Design for Recycling Guidelines for PET bottles have also been introduced as a way to control the additives and the type of labels used in PET bottles in order to allow their recyclability (European PET Bottle Platform (EPBP), 2018).

In regards to the created characteristics, exposure of PET bottles to environmental factors (e.g. temperature, UV, moisture) over a period of time such as from disposal to collection and transport and sorting, can potentially lead to unavoidable deterioration of their physical and chemical properties (Figure 3) (Venkatachalam et al., 2012). Polymers undergo degradation at every stage of their lifecycle (Vilaplana and Karlsson, 2008). Specifically, oxidative reactions lead to the formation of new oxidative functional groups that consume the stabilisers originally added to the plastic, decreasing the stability of the polymer and leading to deterioration of its mechanical properties. This may then enhance the sensitivity of the recyclates to further thermal- and photo-degradation, affecting the recycled material’s future performance (Vilaplana and Karlsson, 2008). Thermal degradation may also be favoured by the synergistic effect of contaminants (e.g. PVC, additives) and moisture that may be present in the PET bottle scraps (Torres et al., 2000), during melting and mechanical injection molding phases. Acids produced due to the presence of contaminants (i.e. PVC, adhesives and additives) and residual moisture from the surface of PET plastic flakes after their washing stage, can decrease the intrinsic viscosity and molecular weight of the polymer during reprocessing due to the hydrolytic chain scission of the co-polyesters at high temperatures (Al-Sabagh et al., 2016; La Mantia and Vinci, 1994; Subramanian, 2000; Torres et al., 2000). This can facilitate the crystallization of recycled PET, which reduces its elongation at break (i.e. makes it more brittle compared to its virgin counterpart) and impact strength (Torres et al., 2000; Venkatachalam et al., 2012). Discolouration may also result due to the formation of various chromophoric systems following prolonged thermal treatment at high temperatures (Venkatachalam et al., 2012).

Removing impurities created during the disposal, collection and sorting stages is important in ensuring that most of the PET bottles can be effectively recycled. Contamination at any of these stages can be avoided if the ability of consumers to separate their plastic bottles effectively at source increases and if the collection practices align with the practices (and maturity of technologies used) at the waste and reprocessing industries. Often using compatibilisers, can enable otherwise incompatible polymers such as PET and PP or HDPE to be mixed together to create new materials with desirable physical and mechanical properties (Genjie et al., 2010; Hahladakis et al., 2018; SPI, 2015). Compatibilisation makes otherwise immiscible polymers to be finely dispersed in the other creating a macroscopically homogeneous mixture with strong resistance to coalescence, through the addition or in situ generation of a macromolecular species that exhibits interfacial activity in heterogeneous polymer blends (Kaiser et al., 2018). Despite the potential benefits of compatibilisation in improving the overall performance of the blend and in creating an advantageous combination of properties and/or the generation of new ones, this technique only enables one additional life cycle to the polymer (Kaiser et al., 2018). Burning materials recycled by compatibilisation in an energy-from-waste plant is considered to be the optimal route; therefore this technique should be avoided in a circular economy whenever possible.

Although trivial, the single-use plastic bottle example demonstrates the applicability of the typology developed in providing a structured way of understanding quality aspects associated with MCPs lifecycle. In addition, it highlights the typology’s usefulness in generating insights into potential interventions that could be introduced in practice for designing out different types of wastes.

5. Concluding remarks

The perceived low quality of MCPs recovered from waste has prevented them from competing with their virgin counterparts, hindering the formation of strong partnerships between the resource reprocessing industry and the manufacturing sector. At the same time, insufficient partnerships between resource reprocessors and manufacturers has been driving resource inefficiency at both ends of the system. Any attempt to become more resource efficient and close the material loops via retaining the quality of MCPs in the system requires forging of strong collaborations and innovative partnerships between these stakeholders, that must be constructed based on shared values, perceptions and interests.

The quality assessment of MCPs at both upstream and downstream of the point where they are disposed of as wastes is paramount in the transition towards a circular economy, and can be both intrinsically objective and subjective. The degree to which the subjective factors prevail over the objective ones must be regulated for viable and meaningful interventions to be made. The typology developed for assessing MCPs quality based on their inherent, designed and created characteristics and the technologies/conditions/processes/motives used at, and/or associated with each stage of the supply chain can be a useful preliminary step in guiding this process. While in this article we used the single-use plastic bottle as an example, the typology developed can be applied to any type of MCP. It is important to emphasise, however, that the typology can only be used as a screening tool; a multi-dimensional value assessment of the positive and negative impacts associated with systemic interventions must be carried out for sound decision-making.

Gaining objective insights into MCPs remaining functionality and value, and identifying changes that can be made on product design, manufacture, use and management, can unveil and inform well-targeted, strategic ways of promoting circularity. To support this typology, we need a method that looks at each MCP individually and assesses how its redistribution back to the supply chain is affected by its very own design and lifecycle, and by those who control it. This is in line with new economic analysis approaches that focus equally on production and consumption of MCPs. These approaches advocate that perspectives on the production-consumption of MCPs should not be collated to derive a general theory applicable to groups of MCPs, but should be individual and specific. This type of assessment can provide an indication of what is practicable and reasonable to be changed based on forward and reverse logistics set-ups for a specific MCP, as well as on area-specific conditions, cultures and practices.

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