Contaminated interaction: another barrier to circular material flows

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Abstract

Contamination poses a significant problem to the circular economy, which derives much of its value from maintaining pure material flows. The aim of this paper is to frame contaminated interaction among other forms of contamination and investigate its effects on the circular economy. The research is based on a review of the contamination literature and case studies. We differentiate between three types of contamination influencing circular material flows: technical, which deals with fitness for use; systemic, which deals with efficiency in processing; and interaction, which deals with user-object interaction and decision making. Our focus is on developing a foundational understanding of contaminated interaction and how it influences circular processes. Through multiple examples, contaminated interaction is shown to create three barriers to the circular economy: downcycling, disposal and hindered circulation. Among other proposals to address contaminated interaction, the research calls for the development of experientially transferrable design—products that can move between users and uses without negative consequences.

Introduction

In modern markets, millions of objects move between uses and users every day. The longer these objects stay in use, the better the raw materials utilized in their manufacture are exploited. Maintaining the *perceived* value of objects after use then becomes increasingly important. In the retail market this is readily seen through the example of wardrobing—the act of temporarily using an object, such as an item of clothing, and then returning it to the store. The object is used enough that it cannot pass as new but is still returnable. Stores sell these items at a discount, give them away, or discard them. In the US retail industry, the result is an estimated $16 billion loss each year (Speights and Hilinski 2005). Treating used objects and substances differently is common. For instance, people rid themselves of worn bills faster than crisp ones (Muro and Noseworthy 2013) and water, once recycled, may be seen as unfit for consumption(Rozin et al. 2015). These examples highlight the phenomenon of contaminated interaction—a user-object interaction influenced by prior use (Baxter et al. 2016a, 2017).

The aim of this paper is to explore the concept of contaminated interaction as it relates to circular material flows. We first differentiate between three types of contamination affecting such flows: technical, systemic and interaction. Next, we focus our attention on contaminated interaction and unpack the factors that drive it. We then show how closed-loop material flows—broadly referring to raw materials, substances, components, or products—are particularly vulnerable to contaminated interaction since the perceived meaning of an object changes as it moves between uses and users. Specifically, contaminated interaction is shown to cause object avoidance, devaluation, and misuse resulting in impeded material circulation. Lastly, we present case studies to show how contaminated interaction can influence the processes of reuse, remanufacturing, and recycling. This understanding provides a foundation for maturing knowledge around the contaminated perceptions of goods and how this influences system-wide processes. The successful realization of a fully-developed circular system requires that we understand and account for such contamination (Hood 2016).

Contaminated Circularity

To contaminate means to make something impure. This assumes that what is contaminated deviates from a pure or undefiled ideal state (Duschinsky 2011). In the natural world, objects are considered contaminated when something else interacts with them or they are considered for some purpose. For example, a piece of land may be contaminated after a factory has discharged chemicals on it. Likewise, untouched land may be deemed contaminated and unsuitable for human use due to the naturally occurring presence of radon gas which can lead to cancer (Darby et al. 2005; Krewski et al. 2005). In the artificial world, the pure state is designed through human intervention. For instance, raw materials must often be processed to separate the desired products from the undesired by-products (Baumgärtner and Arons 2003). In this case, the refined material becomes a pure output per engineering specifications. Deviation from this can lead to a perception of an impure and contaminated state. Such deviation is bound to happen as desired specifications change with time or as the material is altered with use. Thus, most material flows begin with some judgment of purity to produce products suitable for use. In closed-loop systems, secondary processing further exacerbates this situation giving rise to incremental impurities. In a circular economy solution where cycling of material flows provides repeated value, such impurities pose an implementation challenge and can add cost or complexity to the cycle or may even invalidate it.

To further understand contamination as it relates to the circular economy we conducted a literature review. The search was carried out using Scopus with the keywords “circular economy”. Papers were scanned for relevance to some form of contaminated material flows. Emerging forms of contamination were iteratively determined and the search continued until saturation was reached. In total, 82 publications related to the circular economy and contamination were identified and reviewed. Saturation was determined when no new forms of contamination emerged and this occurred when approximately 40% of the publications were examined. The review converged around three forms of contamination which we have called technical, systemic, and interaction contamination. Additional literature was later sought to reinforce specific points. A summary of the three types of contamination is given in Table 1 and each is now described in detail.

Table 1 Types of contamination within the circular economy

Contamination Type	Definition	Circular barrier(s)	Areas of occurrence
Technical	The presence of a contaminant or altered physical property that render material unfit for use	Disposal, downcycling, hindered material flows	Any point in a material life-cycle
Systemic	The presence of a contaminant or altered physical condition that renders material flows inefficient	Inefficiencies in material flow	Throughout system-level processes
Interaction	The presence of some real or imagined property which alters how a user perceives and engages with a material	Disposal, downcycling, hindered material flow	Any user-object interaction

Technical contamination deals with impurities already existing in objects or those transferred from contact with a source contaminant that renders a material unfit for use. For example, contaminants may enter a factory, be transmitted to workers, or be expelled into the environment (Hojas Baenas et al. 2011). Here the concern is about the fitness of materials for use, i.e. how the presence of contaminants renders raw materials less usable, processed products unfit for use, and the processing of products harmful to people and the environment (Green 2006; Krook et al. 2006; Yuracko et al. 1997). As such, technical contamination can be considered at any point in the material life-cycle and can be measured and evaluated objectively against a pure state of the material. This pure state is determined and evaluated according to the desired characteristics set forth by companies and regulatory bodies. In a circular system, these evaluations will increasingly be needed within each cycle of use as value diminishes and materials need to be downcycled to relevant applications (Birat 2015; Haas et al. 2015; Koffler and Florin 2013; Verhoef et al. 2004).

Systemic contamination is concerned with impurities in the flow of materials within a system. For example, difficulties in separating materials at end of life may lead to impure material mixes that are costly and inefficient to reprocess (Klausner et al. 1998). Here the concern is related to the efficiency with which materials are intended to move within a system (Klausner et al. 1998; Gregson et al. 2015; Ongondo et al. 2013). As such, systemic contamination can be understood through a system-level analysis and is considered against the ideal of how materials flow within such a system. This problem grows with the transition towards a circular economy. For instance, one hurdle to utilizing discarded ICT components collected and processed for secondary use is that components are often stripped of vital elements before they are donated (Ongondo et al. 2013). Systemic contamination surfaces in material streams, not at the individual product level. The stakeholders most concerned with this form of contamination are those dealing with supply chain considerations in distributing, collecting and processing materials. This is a reason why design for disassembly is a key element of circular economy thinking (Andrews 2015; Winkler 2011).

Contaminated interaction is concerned with impurities in an object's perceived value due to prior use. For example, many consumers exhibit repulsion and disgust toward types of remanufactured products (Abbey et al. 2015b, 2015a). Here the concern is behavioral and deals with how user-object interaction and decision making change as objects move through multiple uses and between users (Andrews 2015; Bardhi and Eckhardt 2012; Hood 2016; Liu et al. 2009; Baxter et al. 2016b). It, therefore, refers to a user-object interaction, which is contaminated because it deviates from an intended interaction. The intended interaction from which the deviation occurs is either: a) a desired interaction (e.g. riding in a clean car is a more satisfying experience compared to a dirty car); or b) a typical interaction (e.g. worn money is spent faster compared to crisp currency (Muro and Noseworthy 2013)). As such, contaminated interaction can be understood through an analysis of user-object interactions throughout a system. The interaction becomes contaminated following a real or imagined change in an object's state. Real changes come from physical alterations or contact with some source contaminant. Imagined changes occur with mental associations. The prior interaction may originate as an object gets passed between multiple people, or as it moves through use(s), or may be influenced by an outside factor such as surface changes due to UV degradation. Contaminated interaction can act as a barrier to the circular economy by negatively altering individual decision making. An example of this is the repulsion towards remanufactured products that may disqualify such products from further circulation.

These types of contamination are unique in what they affect and the mechanisms through which they influence the circulation of material flows. The types of contamination can coexist so they should not be viewed as mutually exclusive. Each type of contamination can also occur in isolation. For example, the presence of chemicals in food packaging may make it unsuitable for use but, if imperceptible, will not affect user interaction and systemic contamination. All modes of contamination create barriers to the circular economy and should be mitigated.

Contaminated Interaction

For contaminated interaction to occur, the perceived change in the object must be meaningful. Meaning originates from an individual's perception of an object, is socially constructed, guides how the object is interacted with, and can change as the object moves through its life (Krippendorff 2005). Accordingly, to understand contaminated interaction, we must first understand how meaning alters while users engage with objects.

Prior work has linked contamination to maintaining personal health (Muro and Noseworthy 2013; White et al. 2016; Hejmadi et al. 2004), and interpersonal space (Argo et al. 2006, 2008; Belk 1988; Goffman 2009). In previous research, we have grouped these in categories of hygiene and territory respectively, but have also linked contamination to utility (Baxter et al. 2017, 2016a). Hygiene is about preserving one's health. Territory is about including or excluding desired people or objects from personal space. Utility is about how changes in an object increase or decrease its technical, aesthetic, economic, and social value (Aurisicchio et al. 2011). The sensitivity and realization of these drivers is shaped through culture and personal experience[i]. Together, these elements influence meaning and drive subsequent interactions. An understanding of these three drivers provides a basis for building and testing hypotheses around contaminated interaction. Importantly, contaminated interaction occurs at the individual level. This means that it is prevalent in consumer markets but it is also seen in business to business exchanges to the extent that decisions are made by individuals.

Hygiene considerations respond to feelings of disgust which is thought to be an evolved revulsion to internally-harmful substances such as pathogens (Curtis 2013; Curtis et al. 2011). Accordingly, feelings of contamination tend to increase as the object becomes more intimate (e.g. closer to bodily intake) and has a higher chance of carrying a harmful substance (O'Reilly et al. 1984; Abbey et al. 2015b, 2015a). Instances in which products become more hygienic are rare so hygienic issues are nearly always negative, e.g. the feeling that pre-owned goods are not clean enough to buy or use. Feelings of disgust and the potential for contamination do, however, decrease if the source is familiar such as a loved one (Nemeroff 1995).

Territory considerations respond to cultural and personal habits of establishing and defending a desired personal space. Personal space can be enhanced or threatened with physical elements such as smells, noise, and markings (Goffman 2009) and non-physical elements such as things valued or devalued because they have been touched by another person

(Belk 1988). Such considerations tend to be negative since personal space is often threatened, e.g. avoiding second-hand goods because they carry the *essence* of the prior user. However, positive contamination may occur when the contaminant has strong, positive qualities such as an attractive person or a celebrity (Newman et al. 2011; Argo et al. 2008; Nemeroff and Rozin 1994). Alternatively, positive contamination may occur as an individual's personal space becomes more pleasant.

Utility considerations respond to an assessment of the functional value of an object. Functional value can relate to the technical ability of an object to perform a task, or it can relate to other functional elements such as the social, aesthetic, or economic needs of the user (Aurisicchio et al. 2011). While utility issues often cause negative contamination, e.g. used products being perceived as unreliable, there are several examples in which utility increases with time and use, creating positive contaminated interaction. For instance, some home buyers prefer used homes to avoid issues that arise in the first few years of a home's life. Other products are made to become more aesthetically appealing as they age. As is the case with the hygiene and territory drivers, however, the original designed product and interaction typically diminishes with time.

An investigation of positive contamination is beyond the scope of this paper as our interest is in how contaminated interaction acts as a barrier to circular flows. Contamination is generally negative since objects are typically designed to a high specification, which diminishes with time and use. This is exacerbated by a negativity bias in which negative stimuli have a greater psychological effect than neutral or positive stimuli of the same magnitude (Ito et al. 1998; Peeters and Czapinski 1990; Rozin and Royzman 2001).

Contaminated Interaction as a Barrier to Circular Processes

To understand how contaminated interaction influences circular material flows, we examined 14 case studies, see Table 2. Nine of the case studies involved interviews with either users or service providers, see case studies marked with a star (*). The cases were selected to provide a broad view of how contaminated interaction unfolds. Specifically, they cover occurrences of contaminated interaction in relation to vehicles for people and goods transportation, consumer electronics, clothing, children products, sporting equipment and packaging.

Table 2 Summary of case studies investigated

Case	Description
Water reuse*	Used water, even if thoroughly treated, is viewed as either not at all usable or suitable for secondary uses only.
Car sharing*	Shared cars often cause negative experiences or are avoided altogether due to the actions of prior users.
Baseball	Baseballs used in a game, if questioned in terms of integrity, are taken out of circulation and used as practice balls.
Toy sharing	Shared toys often raise concerns in parents as they are perceived as unclean and damaged resulting in hesitation to join such programs.
Cloth Diaper service*	Used cloth diapers are accepted by parents only when they have been used by their own child but are considered unsuitable if they have been used by another child though professionally cleaned.
Recycled textile*	Recycled textiles, even when taken down to the fiber and fundamentally reprocessed, reportedly cause disgust and are not being bought.
Wardrobing	Gently used items are returned to stores but can no longer be passed as new and are subsequently sold at a discount, passed on to secondary markets or disposed.
Forklifts*	Remanufactured forklift trucks covered by warranty are still seen as lower quality and are sent to secondary markets.
Mobile phone	Remanufactured phones, despite coming with warranties, are stigmatized leading to phones being sold at a discounted price.
Food processors	Remanufactured food processors are thought to still be unclean even though they have gone through an entire industrial reprocessing.
Packaging recycling*	Used and altered packaging is often seen as waste leading to lower recycling rates.
Clothing take-back*	Used cloths are discarded to second hand stores because they are seen as no longer carrying value.
Littering*	Used objects with altered characteristics influence littering and lead to lower return rates.
Baby equipment*	Used baby equipment exchanged in second-hand markets often see personal parts replaced as they are perceived as unclean.

*included interviews with users or service providers

Three barriers to circular material flows emerged from the analysis of the case studies, namely downcycling, disposal and hindered circulation, see Figure 1. The barriers are depicted over a simplified linear economy model in which *raw material* moves into *manufacture*, and *use*, and ultimately becomes *waste.* The return flow entails a circular economy model based on the *reuse*, *remanufacture* and *recycle* of materials. Manufacture refers to the initial manufacturing of a product but can also include services (e.g. facilitated redistribution) or manufacturing needed to reintroduce a product into the market. Use includes both primary and secondary use within the same or alternative markets. The barriers result from individuals' evaluation of new or used objects prior, during, or after consumption. Contaminated interaction is relevant to companies or business to business transactions when individuals in organizations hold biases around contamination. Evaluation of objects is informed by aspects as varied as previous use, other users, accompanying objects, object settings and the perceptible characteristics of the object (Baxter et al. 2016a). The three barriers to circular material flows are now illustrated in turn.

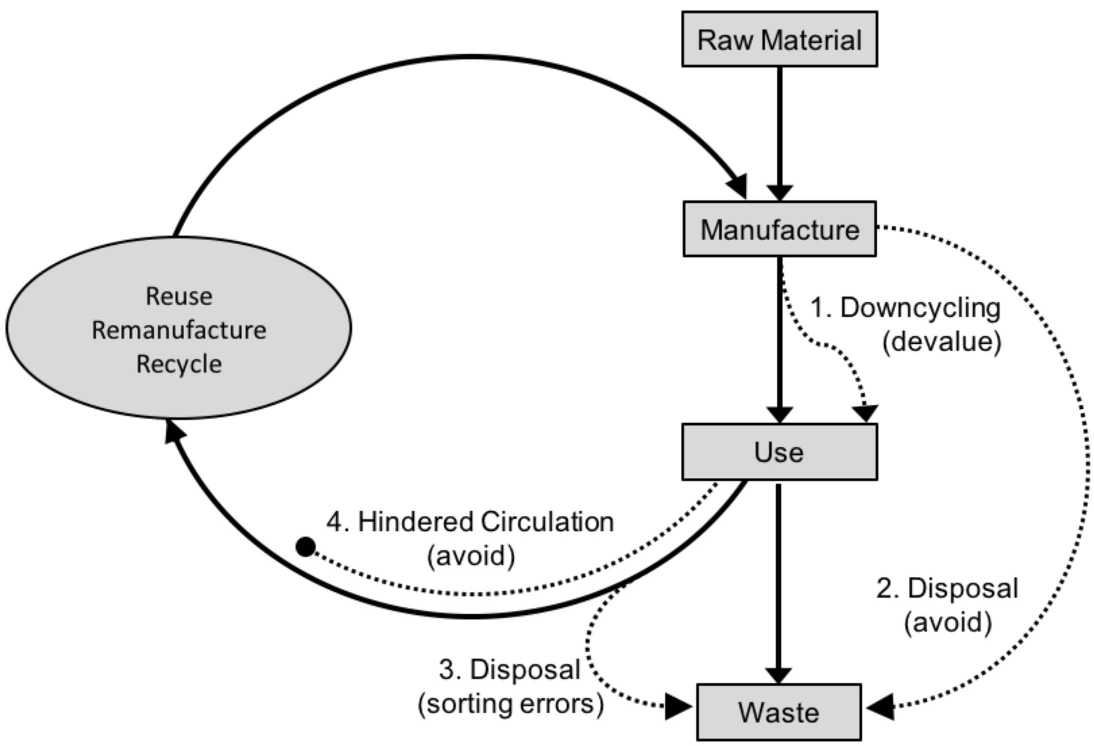

Figure 1 Barriers to circular material flows caused by contaminated interaction.

Downcycling: Evaluation prior to purchase and use may lead to products or substances losing their value because of contaminated interaction concerns. This can result in manufacturers and service providers downcycling products to secondary uses and markets, see dotted line 1 in Figure 1. Downcycling to secondary uses is common but in this case, differs from standard downcycling in that it is driven by user perception, not an objective change in value. For instance, recycled water is not seen as suitable for domestic use (Gu et al. 2015). Downcycling may also send products to secondary markets, e.g. remanufactured forklifts sent to developing countries. This is also a form of downcycling since a secondary market claims a fraction of the original value.

Disposal: Disposal takes place in two ways. During evaluations of objects prior to purchase and use, individuals may make decisions to avoid products, e.g. an aversion to used clothing due to concerns of contamination. If supply of such products exceeds demand (including demand in secondary markets), the material may be disposed of in the landfill, see dotted line 2 in Figure 1. Disposal can also result from end-of-life evaluations. At this point, decisions must be made to sort waste objects, e.g. recyclable packaging, so that they are properly returned to the system. Contaminated interaction has the potential to lead to sorting errors that can result in increased disposal of otherwise circular materials, see dotted line 3 in Figure 1. This material is often thought to be prematurely disposed as it is sent to landfill rather than through a circular process such as recycling.

Hindered circulation: Early decisions made by users to avoid products can hinder a business from identifying a sufficiently strong demand to pursue or expand circular business opportunities, e.g. unwillingness to engage in a cloth diaper service despite professional cleaning, see dotted line 4 in Figure 1. This includes the creation of new opportunities and the expansion of existing operations.

Case Studies of Contaminated Interaction in Circular Processes

In this section, we present examples of contaminated interaction through a selection of the case studies investigated, and show how they influence circular processes. We consider cases of contaminated interaction across three process categories: reuse (Liu et al. 2009;

O'Reilly et al. 1984; Catulli et al. 2013; Baxter et al. 2015a; McCracken 1986; Hood 2009; Kapitan and Bhargave 2013; Argo et al. 2006), remanufacture (van Weelden et al. 2016; Abbey et al. 2015b, 2015a; Agrawal et al. 2015; Andrews 2015), and recycle (Gu et al. 2015; Rozin et al. 2015; Hood 2016). For each process, we highlight a specific case where contaminated interaction occurred, some strategies to deal with it and its impact on circular material flows (see summary in Table 3). The cases presented in the paper were chosen to highlight variations in how circularity is impacted and therefore provide a perspective on the breadth of the phenomenon.

Table 3 Summary of detailed contaminated interaction cases

Process	Case	Presence of Contaminated Interaction (driver)	User Interaction	Circular Impact
Reuse	Car sharing	Smoke residue in car creates feelings of disgust (hygiene) and infringement of personal space (territory)	Avoid	Hindered circulation
Remanufacture	Forklifts	Perceived to be of lower quality (utility)	Devalue	Downcycle
Recycle	Packaging	Altered packaging is seen as waste and discarded rather than recycled (utility)	Sorting errors	Disposal

Reuse

The European Union Waste Framework Directive defines reuse as "any operation by which products or components that are not waste are used again for the same purpose for which they were conceived" (European Union 2008). Under this definition we consider reuse including the sharing of objects among multiple users, the redistribution of objects through second-hand markets, and the extension of a product's life by continuing to use an object after its initial intended use. We exclude remanufacturing and recycling operations, which require additional processing capability. To explore how reuse is threatened by contaminated interaction we consider the case of car sharing.

Car sharing is a fast-growing trend in which a group of individuals gain access to a set of cars owned by a company. These cars are typically used in urban environments for short trips around a town. The short duration of the trips means that several users often ride the same car in a single day making it particularly susceptible to contaminated interaction.

In a study of car sharing, Bardhi and Eckhardt (2012) found evidence of contaminated interaction. One user described the gross feeling he had when using a car previously used by someone who had broken the non-smoking ban. This sentiment is supported by community blogs and online reviews. On one blog, an individual reported that 16 of the last 20 times he used a car sharing service the vehicle was saturated in smoke (Petworth 2016). Smoking residue is a form of technical contamination, which subsequently causes contaminated interaction. At the root of the dissatisfaction felt by these users seems to be a hygiene concern around maintaining personal health as well as a territorial concern around an uncomfortable personal space. The result is that car users are distancing themselves from the overall community (Bardhi and Eckhardt 2012) or considering different services altogether (Petworth 2016). This shows how contaminated interaction can lead to service substitution or avoidance.

Car sharing rules act as a strategy to prevent contaminated interaction. For example, when new users sign up to the Zipcar car sharing service they are shown “six rules of the road” to which they agree: report damage, keep it clean, no smoking, fill ‘er up, return on time, and pets in carriers (www.zipcar.co.uk/is-it/rules). Rewards or punishments are used to encourage good behavior. The company, however, is still unable to ensure satisfactory user experiences in a consistent way, as seen in various user comments (Petworth 2016; Bardhi and Eckhardt 2012), resulting in potentially poor brand reflection. This may have the secondary effect of deterring other companies from running similar programs or preventing expansion of existing offerings into additional market segments.

Remanufacture

As the British Standards Institution defines it, remanufacturing is to “return a used product to at least its original performance with a warranty that is equivalent or better than that of the newly manufactured product” (BS 887-2:2009). Within this section we include refurbishment and significant repair intended to return an object to a satisfactory state. Remanufacturing is a step below reuse because it requires additional work and raw material to get the object into a usable state. In remanufacture, the object maintains its fundamental characteristics and thus is distinct from recycle. To explore how remanufacture is influenced by contaminated interaction we look at the case of forklift rebuilding.

As part of a research project, one of the authors of this paper worked with a forklift truck manufacturer which was interested in having remanufactured trucks among its offering to create a more circular business model. A remanufactured or reconditioned forklift truck can cost a fraction of the price of a new unit (Chapman et al. 2009). Remanufacture of a forklift truck includes disassembling it, heat-cleaning it, inspecting components for defects, resurfacing and resizing components and replacing others, reassembling and testing. Buying a remanufactured forklift truck may cause worry and apprehension, however, as there is a risk of pre-existing damage.

The forklift manufacturer consulted explained that remanufacture has significant benefits. Among these is the fact that the product often performs better than new units because most failures happen in the early stages of the product and those would be resolved if the product is still around for remanufacture. Despite this, when discussing the possibilities for remanufacture, the company indicated that users would not be likely to accept a remanufactured unit because of the perceived defects caused during previous use. Wear and defects on used units are changes to the physical aspects of a product, which then cause the contaminated interaction. This reflects a utility concern as it represents a perceived decrease in functional value. The company explained that they would only be able to sell remanufactured units to secondary markets such as those in developing countries. This shows how contaminated interaction can lead to downcycling in terms of market. It is worth noting that even those products that are popularly remanufactured (e.g. mobile phones) and have guaranteed 'like-new' quality assurances complete with a company-issued warranty are sold at a discount. In other cases, remanufactured products are considered to continue to carry some kind of germ from prior use (Abbey et al. 2015b). All other variables accounted for, the only reason for these altered appraisals is contaminated interaction.

Strategies to overcome negative perceptions of remanufactured parts partially deal with addressing perceived risks of acquisition through approaches such as quality assurance (Ongondo et al. 2013; van Weelden et al. 2016). In other cases, however, there is much less that can be done, e.g. remanufactured food processors perceived as disgusting and unfit for secondary use, in which case it is recommended to turn attention to recycling and recovery of materials from the product (Abbey et al. 2015b, 2015a).

Recycle

The European Union Waste Framework Directive defines recycling as "any recovery operation by which waste materials are reprocessed into products, materials or substances whether for original or other purposes" (European Union 2008). Within the scope of recycling we include the operations of disposing, collecting, sorting, and subsequently reprocessing materials and substances. Recycling is considered to be energy intensive and is, therefore, the lowest option of a sustainability hierarchy (EMF 2013; European Union 2008). To explore how recycling is influenced by contaminated interaction we examine common packaging disposal practices.

The familiar nature of many recyclables means that high rates of correct recycling is typically achieved in developed markets. However, as objects move through use, their size, shape, color, or other characteristics may be altered. In turn, this can lead to changes in what the object means to the user and how the user interacts with the object. Such changes significantly alter the subconscious categorization of packaging from recyclable to trash (Baxter et al. 2016b). In a study of disposal behavior, commonly recycled objects, once altered, have been shown to be recycled less than half as frequently (Trudel and Argo 2013). The changed meaning of commonly recycled objects shows two forms of contamination. Contaminated interaction emerges as the intended interaction with the object changes due to some prior modification made upon the object, e.g. torn or cut paper and a crumpled soda can. This is unique in that it is a case of self-contamination since the individual disposing of the object is often also the one who creates the object alterations during use. In this case, the fundamental value of the object is diminished in the eyes of the user representing a form of utility concern, which then leads to sorting errors. While the sorting errors result from contaminated interaction, they lead to systemic contamination since the object can be erroneously sorted and thus does not adequately enter the value stream.

Three strategies are identifiable to deal with this. First, signage on the bins could be changed to resemble altered objects to nudge proper sorting (Trudel et al. 2015). The packaging itself might also be redesigned to control transformations undergone during use (Baxter et al. 2016b). A third strategy would be to make disposal a more conscious endeavor.

Discussion and Implications for Industrial Ecology

This research has made a case for how contaminated interaction can act as a barrier to circular material flows. Contaminated interaction is believed to stem from variations in the perceived state of a material and driven by concerns over hygiene, territory and utility. This form of contamination can hinder the circulation of materials, result in downcycling or lead to disposal. These barriers were identified from examining 14 case studies and shown to influence decision making by individuals in consumer and business to business environments. This list of barriers is meant to be exhaustive but further research should validate the existence of the barriers in more situations. We expect technical and interaction contamination to share the same barriers and differ only in evaluation context (i.e. what is being evaluated and by whom). Systemic contamination, like technical contamination, can be objectively assessed though we expect this to primarily deal with the efficiency of material flows.

In direct analogy to thinking in industrial ecology[ii], contaminated interaction needs to be addressed in several ways. Methods should be identified to limit or eliminate contaminated interaction at a *design*, *use*, *service* and *policy* level.

Design processes should consider how object meaning changes with multiple uses and users. This follows the call for emotionally durable design—a form of sustainable design that enhances the durability of relationships between people and products to reduce consumption and waste (Chapman 2005). The present research suggests that we need to expand this approach to consider how to design products that easily transfer between uses and users while maintaining high perceived value. This *experientially transferrable design* considers emotional durability but also the resilience with which a product can be used by multiple people and maintain a positive (or at least neutral) user experience. An example of this is seen in cars which adjust mirrors, seat positions, radio stations and other settings to a specific driver helping develop feelings of ownership and personal space (Baxter et al. 2015b). This assisted personalization helps car sharing users have a more pleasant experience.

In terms of *use*, some interventions are focused on setting and monitoring behavior. For example, communities in which multiple users share spaces or products, such as Airbnb and Zipcar, increasingly rely on rules explaining how objects are expected to be used. Financial or social penalties, e.g. fines or bad reviews, are set up to discourage misuse. In other examples, simply monitoring user behavior is a strategy to reinforce appropriate use. Installing smoke detectors, CCTV or human monitoring systems are all examples of this. Finally, interventions may also prevent object changes in use, e.g. through designing for durability as is seen with the relatively more durable bicycle design used in bike sharing programs.

Services can help to return contaminated goods to a valuable state. Some physical elements of contaminated interaction may be addressed through common practices such as cleaning and maintenance. However, this is just one aspect of the problem. The non-physical elements of contamination may be much harder to address (Hood 2016; Abbey et al. 2015a). In these situations, it may be necessary to provide users with selective information. Online shops often provide substantial information to assess the quality of a product. It is important to appropriately communicate other indicators of quality. This communication requires further examination since some tactics, such as labeling the item as 'good as new', have the adverse effect of making people think about how someone previously used it (Ackerman and Hu 2016).

Policy should do more to protect buyers and sellers from the adverse effects of contaminated interaction. An example comes from the buying and selling of homes. Sellers are typically required to disclose any material defects that could influence purchasing decisions to protect buyers. Such defects are typically considered in a physical sense (e.g. damage to the home) but may also include psychological defects of so-called stigmatized properties (Alias et al. 2014). A stigmatized property is "psychologically impacted by an event which occurred or was suspected to have occurred on the property, such even being one that has no physical impact of any kind" (Morgan 1994). Property stigmas can come from any number of factors such as criminal activity, murder, diseases carried by the previous owners, and, in some cases, even the presence of ghosts (Reilly 2000). In the US, about half of the states have laws regarding stigmatized property and these most often protect the seller from any liability if they fail to disclose such issues (Larsen and Coleman 2001). Similar treatment is given to other stigmatized goods that might otherwise be circulated[iii].

Conclusions

If widespread adoption of the circular economy is to be realized, we must better understand the barriers posed by contaminated material flows. In this paper, we have differentiated between three types of contamination, namely technical, systemic and interaction contamination. Technical contamination and systemic contamination provide an incomplete picture of how material flows can be threatened. To better understand and support material flows in the circular economy, interaction contamination also needs to be studied and considered in the design process. Each contamination type can have different causes, impacts and necessitates the attention of different parties to be mitigated. The advantage of differentiating between these three types is that new understanding of how circular processes are affected by contamination is gained.

In this research, we have proposed a theoretical foundation for contaminated interaction and shown how it can influence the circular economy. Contaminated interaction is established as an important concept complementing the traditional technical-view of contamination with a novel perspective centered on user-object interaction. The analysis showed how contaminated interaction can lead to *hindered circulation* of material, *downcycling* and *disposal*. This highlights the need for *experientially transferrable design*—products that can be transferred between uses and users without negative influence on user behavior and interaction. This research advances the field of industrial ecology and circular economy with holistic and multi-level understanding of contamination, which has the potential to positively influence the design of circular systems. It contributes to the field of user experience with novel understanding of user-object interaction in the context of reused objects. The outcomes of this research suggest that a new mind-set is needed to address the barriers posed by contaminated interaction.

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[i] The importance of cultural frames in categorizing and interacting with products has been shown in work by Mary Douglas (2003). Douglas argues for a spatial construct of dirt and pollution in which those things considered dirty are examples of “matter out of place.” This view of dirt requires a system through which it is evaluated. As Douglas writes, “dirt is the by-product of a systematic ordering and classification of matter, in so far as ordering involves rejecting inappropriate elements.” We have adopted a similar stance in that objects deemed contaminated are evaluated against some context. This is true of technical, systemic, and interaction contamination. We further posit that the contaminated interaction drivers of hygiene, territory and utility are shaped through contextual frames of what is appropriate or ideal. This is most evident with utility considerations in which the object is created for some objective and subsequently has some embodied context against which it can be evaluated. We differ from Douglas’ particular view of cleanliness and hygiene in that we find mounting evidence for an evolutionary basis for disgust. Thus, in the hygiene example, there is some absolute determinant of what is deemed disgusting though this will be shaped through contextual factors.

[ii] The development of contaminated interaction within industrial ecology shares several parallels to closed-loop development of metal processing as presented by Verhoef, Dijkema, and Reuter (Verhoef et al. 2004). For instance, just as the impurities in a few ores (zinc, copper, and lead) shaped the industrial infrastructure for metals processing, we believe that some key cases of contaminated interaction will shape human-facing processes of the circular economy. This will include the treatment of materials before use, the information kept about specific materials and their histories as well as terms of use of objects. Just as with metal processing, the development of such an infrastructure will require the close collaboration of designers and operators. Finally, we suspect contaminated interaction will follow metal processing in terms of the depth of understanding developed around circular processes.

[iii] For instance, eBay restricts sellers from listing objects owned by murderers or Nazi leaders (see the list of restricted items on www.ebay.com). Bruce Hood also discusses a number of contaminated goods perceived to be unfit for use from homes of murderers to clothing owned by the same (Hood 2009).

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