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Consumer decisions to repair mobile phones and manufacturer pricing policies: The concept of value leakage

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ABSTRACT

Mobile phones have become 'essential-to-have' devices for information-gathering and social communication. They are being technologically advanced, while they are readily available at affordable prices. This motivates consumers to upgrade their mobile phones more frequently. Given these considerations and the lack of accessible repair services, mobile phones have a relatively short life span. The underuse of mobile phones, despite the fact that they are made durable, may result in losses or value leakage. In this study, a probabilistic approach is proposed to quantify the value leakage that may occur due to consumer's decision to not repair broken mobile phones and simply replace them with new ones. A group of 208 mobile phone users has been surveyed to capture consumer's time-dependent willingness-to-pay for repair services. Then, consumer's repair behavior is combined with manufacturer's repair service pricing strategies to calculate the probability of repair or replacement decisions over the life span of mobile phones. Finally, the total expected leakage risk is derived for both consumers and manufacturers. For illustrative purposes, it is shown that a manufacturer may lose up to 331 million dollars over a period of five years due to consumers' decisions to not repair their cracked-screen mobile phones and switch to another brand.

1. Introduction

Nowadays, mobile phones have broadband applications rather than a simple communication device (Butler, 2011). The average selling price of smartphones has gradually dropped over the past few years (Jouihri et al., 2017). It is not surprising that the market of mobile phones is likely to be the largest in size among consumer electronics (Scruggs et al., 2016). Given the quantity of mobile phones, it is essential from a circular economy aspect to evaluate the life cycle of mobile phones and find out whether these resources are effectively utilized.

Over the past few decades, profit-driven strategies such as offering successive generations of products (Miao, 2011), shortening products' life span, and increasing the cost of repairs (Laurenti et al., 2016) have encouraged consumers to purchase new devices rather than fixing and reusing their currently-owned devices. A direct outcome of such strategies is a large number of End-of-Use/Life (EoU/L) mobile phones. According to a recently published report by the United Nations University (Baldé et al., 2015), 41.8 Mt of electronic waste (e-waste) – including discarded mobile phones – generated globally in 2014, and slightly collected by official take-back programs. A large proportion of ready-to-collect used mobile phones in developed countries is being dumped in landfills or exported to developing regions and informally recovered. On the other hand, when making a decision about the recovery of collected mobile phones, recyclers merely perform cost-benefit analyses that are not always economically, socially, and environmentally viable for the society. The recycling of mobile phones has the largest amount of economic losses among all considered consumer electronics (Ford et al., 2016) due to the fact that individual components of mobile phones are not fully disassembled before shredding and material extraction.

In addition to the role of manufacturers and recyclers, the impact of consumer behavior should be highlighted too. With respect to the role of consumers, it is essential to distinguish between consumers' actual behavior and their attitude. Consumers might be willing to repair their broken devices, but a number of existing barriers such as costly repair services and insufficient access to repair infrastructures may dissuade them from repair decision. As a consequence, mobile phones are underutilized (Guiltinan, 2009), and both consumers and manufacturers incur monetary losses. Consumers lose the potential remaining useful life of their devices and have to purchase new phones. On the other hand, manufacturers may lose repair profits. In addition, designing

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unrepairable products and offering low-quality repair services affect consumer loyalty and future sales since some consumers look for clues about the degree of repairability and extended warranty time when making a purchase decision (Lemke and Luzio, 2014).

To analytically formulate the concept of value leakage of used mobile phones, this study is focused on the effect of repair costs on consumers' decisions to keep using currently-owned mobile phones versus buying new devices. It should be acknowledged that in addition to repair cost, there are other factors such as service availability, spare parts accessibility, and personal information concern that influence consumers' repair and replacement decisions. A survey study is conducted to capture consumers' willingness-to-pay for repair services and the role of manufacturers' repair services pricing policies. Combining the consumer-manufacturer interactions, it is possible to quantify the value leakage for both entities. In fact, we will show how repair policies can prevent losses caused by not repairing broken mobile phones.

The rest of this paper is organized as follows: the concept of value leakage is introduced in Section 2 and the related literature is discussed in Section 3. The research questions and methodology are explained in Section 4. An overview of the current flow of used mobile phones in the US is provided in Section 5 to better clarify the value leakage concept. In Section 6, the analytical modeling of value leakage is discussed in three steps; exploring consumers' post-purchase behaviors by surveying a group of mobile phone users, investigating manufacturers' post-sale services, and integrating consumers' willingness-to-pay for repair services and manufacturers' strategic behavior. Finally, Section 7 concludes the paper.

2. The concept of value leakage

There is no established definition for the value leakage in the literature. In this section, we introduce the overall concept of the value leakage as follow with the aim of providing a simple tool for evaluating the circularity level of materials contained in mobile phones:

> 'Any intentional or unintentional deviation from the best-known existing recovery method for an EoU/L product may result in a value leakage. The leakage might be found, either implicit or explicit, significant or inconsiderable, avoidable or unavoidable, in forms of economic loss, environmental degradation or social harm that would affect a wide variety of entities, ranging from consumers to national governments.'

The above-mentioned general definition can be tailored based on the scope of the current study as follow:

> 'The consumer decision not to repair a failed mobile phone may result in a value leakage. This leakage can be found in a form of economic loss that would affect both consumers and manufacturers as the primary stakeholders. The magnitude of value leakage is mainly linked to the time elapsed since the technology release date.'

According to this definition, we aim at showing the economic loss as a result of insufficient utilization of values still embedded in mobile phones (e.g., energy and materials). To produce a product, a remarkable amount of energy and resources are consumed during manufacturing operations. However, the values can easily be lost due to improper decisions of consumers and manufacturers on the early disposal of mobile phones. Recycling a reusable phone is a good example of energy and resource loss.

In this paper, a case study of cell-phone that requires screen repair is chosen to explain the concept of value leakage. The stakeholders considered in this paper are consumers and manufacturers, but the value leakage can be conceptualized for other stakeholders such as government, and society depending on their motivations and objectives.

Fig. 1 illustrates the impact of repair on extending the life span of a mobile phone and preventing the value leakage.

From a high-level perspective, the value may transfer from one economy system to another. For example, e-waste is exported from developed regions to developing regions. As a result, the economic values are lost in developed regions and gained by developing regions, while it leads to environmental issues for developing regions due to informal recycling.

The focus of this study is to evaluate the economic loss for consumers and manufacturers. However, in the context of environmental economics, there has been a wide range of studies that have been concerned with showing the economic impacts of environmental issues. To better conceptualize costs and benefits of a policy, strategy, or project, useful schema have been provided in the environmental economic field to evaluate the total impact on human well-being and ecosystems (Atkinson and Mourato, 2008; Pearce et al., 2006). This idea to conflate the economic and environmental values has also been a controversial topic between environmental economists and engineers.

The concept of value leakage can be of interest to manufacturers, not only due to its effect on building consumer loyalty, but also for improving corporate social and environmental responsibility (Cetindamar, 2007). Another motive for Original Equipment Manufacturers (OEMs) is to prevent the scarcity of materials in the future. Outside recovery or out-of-network 'leakage' is becoming a critical problem for developed regions and many OEMs who rely on certain types of rare earth materials for their production. The faster rise of natural resources prices compared to global economic output combined with less predictable commodity prices, and the fact that by 2030, some 3 billion consumers from the developing world will enter the middle class is driving corporate concerns about resource costs (Nguyen et al., 2014). However, due to the ex-ante nature of analyses, Söderholm and Tilton (2012) argued that the material scarcity cannot be a robust basis for designing material efficiency policies, and instead, environmental impact concerns have been suggested as a motive for making such intervention polices. In addition, societal norms and behavior should be addressed when forming environmental policies (Lane, 2014).

The value leakage in mobile phone recovery process may happen in various cases and in different life cycle stages. First, a significant number of EoU/L mobile phones are discarded in trash cans or stored in households for an uncertain amount of time (Silveira and Chang, 2010) due to the lack of consumers awareness about available reverse logistics channels(Yin et al., 2014). As a result, the disposal misbehavior and delay in returning EoU/L mobile phones for recovery operations may impose an additional cost on reverse logistics systems and, furthermore limit phones remanufacturability and the future marketability due to the technological obsolescence. Second, the product may leak from one economy to another. For example, consumers may receive repair services from a third party. This creates a cost or profit loss for the original manufacturer. In addition, the manufacturer may lose consumer loyalty and future purchase opportunities. Third, the net cost of purchasing new phones to have access to the same phone service and functionalities may be higher than the case of repairing them. In this case, individual consumers are bearing an additional cost. The value leakage may happen at the material recovery stage as well. For example, due to the complexity and mix of materials, the full recovery of all materials in the recycling processes is not possible. Finally, the value leakage of all life cycle stages is not just limited to the economic loss and can be extended to environmental damages and human health issues (Sullivan, 2006).

Capturing the total value leakage over the entire life span of a product is very difficult since a significant comparison between the current system and an ideal system is needed. In addition, it is challenging to define the ideal system or 'most-perfect action'. For example, the total amount of gold recovered from one metric ton of used mobile phones is about twenty times greater than that obtained from mining one metric ton of the ore. However, rigorous logistical efforts are needed to collect used mobile phones, while ore deposits are more accessible. Also, it is not certain that extracting metals from used mobile phones would be more eco-friendly than the other approach.

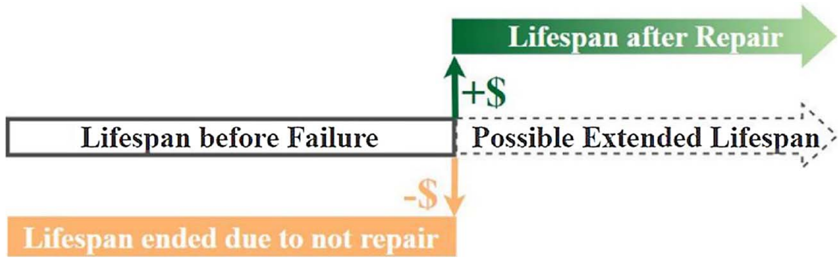

Fig. 1. Possible value leakages over the entire product life span.

3. Literature review

The average use time of a mobile phone has been estimated to vary between 2 and 7 years (Polák and Drápalová, 2012), although other studies have cited different life spans (Herat, 2007; Li et al., 2015), pointing out that the life span of mobile phones has declined over the last ten years. Mobile phones can be possibly used for a longer time than is actually observed among consumers (Huang et al., 2009). Here, the 'life span' refers to the period of time that a mobile phone has been used by its first owner. The life span of a mobile phone can be extended if it finds second- or third-hand users, specifically in developing regions with a huge market for reuse.

Consumers have different reasons to retire a currently-used phone such as perceiving physical obsolescence, having access to the cutting-edge technology, and requiring higher technical capabilities (Ongondo and Williams, 2011). Using a dataset from the Finnish market, Riikonen et al. (Riikonen et al., 2016) identified that the higher technological sophistication – representing the number of features included in the phones – delays the replacement decision, and consequently, increases the use time of the owned phones.

The technology of mobile phones is advancing at a remarkable rate and the time interval between the release dates of two consecutive models is becoming shorter and shorter (Cecere et al., 2015). In addition to the technological progress, the availability of repair services may beneficially or adversely affect the life span of mobile devices. Manufacturers are recently urged by environmental initiatives, e.g. the Digital Right to Repair Coalition, to design repairable products, share repair manuals with end users and independent repair businesses, extend the time horizon of warranty and repair services, and offer convenient waste recovery services. For the case of mobile phones, expensive repair price, unavailability of spare parts, and complicated repair processes have been reported as the most frequent reasons behind unsuccessful repair experiences (Sabbaghi et al., 2017). Manufacturers may not necessarily willing to accept these modifications in the design and after-sale services since some of these strategies may lessen the products sales rates in the short term (Hennies and Stamminger, 2016).

Estimating the demand for repair services during both pre- and post-warranty periods has been the point of attention in the literature (Xie and Liao, 2013). Consumers have some potential propensity to repair products but several barriers discourage them. As discussed in (McCollough, 2009), consumers prefer to spend a limited budget on repairing a product over its life span. Therefore, the pricing of repair services drastically affects the rate of repair (Barrot et al., 2013). Accessibility, availability, and convenience of repair infrastructures are other factors that significantly influence consumer's decision to repair (Houston and Jackson, 2016).

The lack of market for repaired products is an important limitation for the reuse of discarded products, particularly in developed regions (Dindarian et al., 2012). This mainly comes from the fact that the majority of the consumers do not feel confident about the quality of remanufactured products (Matsumoto et al., 2017). As discussed by Cooper and Gutowski, (2017), the efficiency of a reused product depends on its prior deterioration status, and whether the product is restored only or restored-upgraded.

Therefore, it is understood that mobile phones are likely to be underused, leading to at least some economic losses. Even worse, environmental and social issues may be found in addition to economic losses if EoU/L mobile phones are being informally recycled or sent to landfill. Characterizing human-caused economic losses and costs to ecosystems has been addressed by previous studies. For example, Wang and Qiu (2017) have investigated how natural resources such as forests can be affected by land-use decisions during the urban development. In another study, Yan et al. (2017) have quantified the environmental value loss occurred due to excavating materials and infilling of the seabed during the airport construction.

A group of studies has investigated the role of consumers' decisions and manufacturers' policies in e-waste management. To name a few, Tian et al. (2015) have pointed out that consumers' awareness of Extended Producer Responsibility (EPR) strategy and their level of income are correlated to their willingness-to-pay for recycling. Consumers' environmental awareness has been shown to have a central role in effective management of e-waste worldwide (Borthakur and Govind, 2017). It has been observed that direct economic benefits are more likely to lead residents to select a proper disposal method for e-waste in developing countries (Islam et al., 2016). Consumers may not be inclined to accept recycling methods that impose costs on them (Wang et al., 2016). In developed regions, however, the transformation of environmental awareness into sustainable behavior has been problematic (Ylä-Mella et al., 2015). Socio-demographic factors may also contribute to consumers' pro-environmental behaviors (Saphores et al., 2012). In an effort to encourage manufacturers to implement reuse and recycling-based reverse logistics practices, De Oliveira Neto et al. (2017) have shed light on the expected environmental and economic benefits. Improving disassemblability of a design (De Oliveira Neto et al., 2017) and fulfilling future demand through material circulation (Xuan and Yue, 2016) are another example of sustainable strategies that can be adopted by manufacturers.

In this paper, the general idea is to employ preventive strategies against waste generation and profit loss. Minimizing food waste generation by incorporating consumers' preferences (Pirani and Arafat, 2016), employing cognitive theory to capture consumers' waste prevention behavior (Bortoleto et al., 2012), and developing use-oriented business models (Corvellec and Stål, 2017) are a few examples have been concerned with the effective resources use through promoting sustainable behavior. In our study, a probabilistic economic model is developed to quantify the value leakage that may occur in the product lifecycle by incorporating consumers' attitudes towards repair services and manufacturers' repair service strategies.

Our approach to modeling the value leakage is a cost-benefit analysis, conceptually similar to the Total Economic Value (TEV) framework (D. Pearce & Moran, 1994). According to the concept of TEV, ecosystem values for humans are not only limited to direct-use benefits of natural resources. Preserving resources can itself be a value for humans to support the needs of future generations (Loomis et al., 2000). In the current study, we aim to quantitatively clarify the point that repairing mobile phones can preserve materials and energy and can be considered as value.

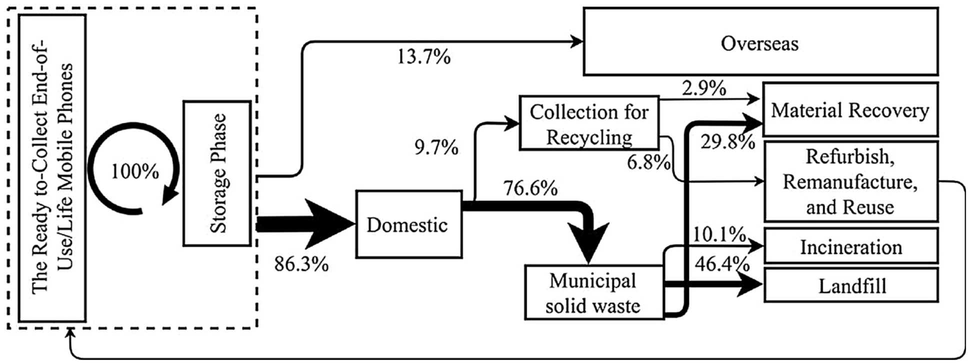

Fig. 2. The estimated flow of End-of-Use/Life mobile phones in the US.

To summarize, there is a little discussion on modeling the concept of value leakage as we have used in this paper. In fact, the prior literature has been mainly focused on managing the collection of used mobile phones (Mutha et al., 2016), improving the efficiency of recovery operations (Franke et al., 2006; Gurung et al., 2013), and advancing the re-marketability of recovered mobile phones (Kwak et al., 2012; Ovchinnikov, 2011), while we aim at finding the value leakage that can be avoided by improving repair services at the middle of life cycle of mobile phones. To the best of our knowledge, this paper is the first attempt to capture and quantify the concept of value leakage resulted from first owners' decisions for the early retirement of broken mobile phones due to costly repair services and the lack of accessible repair infrastructures.

4. Methodology

To quantify the concept of value leakage as a consequence of repair decisions, three main analyses have been conducted:

- First, consumer's repair behavior is captured by conducting a survey. An online survey was sent out to a group of students. Students have been selected as the target group in this study as the representative of younger generations who are the heaviest users of mobile phones among others. In addition, since it has been empirically proved that younger people are less inclined to repair their products (Kurisu and Bortoleto, 2011), the emphasis of the study was on young generations;
- Second, available data on repair service fees have been collected from the website of one of the main vendors of mobile phones in the market to track manufacturers' strategies in pricing repair services over time. A linear model is developed to represent changes in the cost of different repair services offered by the main vendors of mobile phones; and
- Finally, statistical techniques have been applied to derive the analytical expression for the value leakage.

The proposed methodology provides answers to the following questions:

1 How much are consumers willing to pay for the repair services over the life span of mobile phones?
2 How does the cost of a specific repair service change over time?
3 How likely is that a mobile phone is used less than its owner's expected service life (the time period that a consumer expects to use a product)?
4 What is the expected life span of mobile phones according to consumers' willingness-to-pay for repair services?
5 How much do people lose by not repairing broken their mobile phones? How much could consumers' potential repair demand be worth for manufacturers?

The proposed methodology, in fact, integrates consumers' repair behaviors and manufacturers' strategies for repair services to develop indicators representing the risk of underuse of resources. As suggested by Franklin-Johnson et al. (2016), the duration that resources are kept in use can be a measure of the efficiency of consumption.

5. The estimated flows of end-of-use mobile phones in the US

The main research question addressed in this paper is about what economic losses are expected to occur as a result of not extending products' life span. This is different from how the EoU/L mobile phones are collected and recovered. However, we believe that the latter is inseparably linked to the former. To clarify this point, suppose that used mobile phones are basically discarded by their first owners due to costly repair activities. In this situation, collecting discarded mobile phones for material extraction seems to be more beneficial if repairing activities are not economically viable.

Fig. 2 represents the projected national-level flow of the EoU/L mobile phones in the US. Duan et al. estimated that about 176 million units of EoU/L mobile phones were generated in the US in 2010 (Duan et al., 2013). Reported by the U.S. Environmental Protection Agency (2011), the U.S. consumers disposed of 152 million units of used mobile phones in 2010, which is 86.3% of the total generated used phones. Out of 152 million units, 135 million (88.8%) units went into the trash, and the rest being collected for recycling purposes. In 2012, 53.8% of the generated municipal solid waste was dumped in landfills, 34.5% was collected for recovery, and the rest 11.7% was incinerated for energy recovery (U.S. Environmental Protection Agency, 2012). Finally, it is estimated that 30% of professionally-collected used mobile phones are not appropriate for reuse purposes (Hagelüken and Refining, 2008). If we incorporate these numbers, we get a flow map as shown in Fig. 2.

As seen in Fig. 2, only 6.8% of the total EoU/L mobile phones are refurbished, remanufactured, or reused domestically for another life cycle. On the other hand, a significant proportion of used mobile phones is going into landfills resulting in a high volume of material loss. The total loss of materials can be quantified, although this paper is aimed at investigating value losses related to not extending products' life span.

It is worth mentioning that: 1) mobile phones may be stored for an uncertain amount of time before being disposed of appropriately or inappropriately. As a result, stored mobile phones will be less marketable due to the technical obsolescence; and 2) mobile phones may be used in multiple cycles of ownership, leading to an extension of life span. The box 'Usage Phase' implies these two points although Fig. 2 represents the flow of EoU/L mobile phones from a static point of view. In this phase, mobile phones are stored for an uncertain amount of time or reused for another cycle. Reuse and storage phases of used mobile phones can be possibly included in material flow analyses (Oguchi et al., 2008), helping to measure the associated lost economic value. In Section 6, we focus on the value leakage of failure to repair in the first

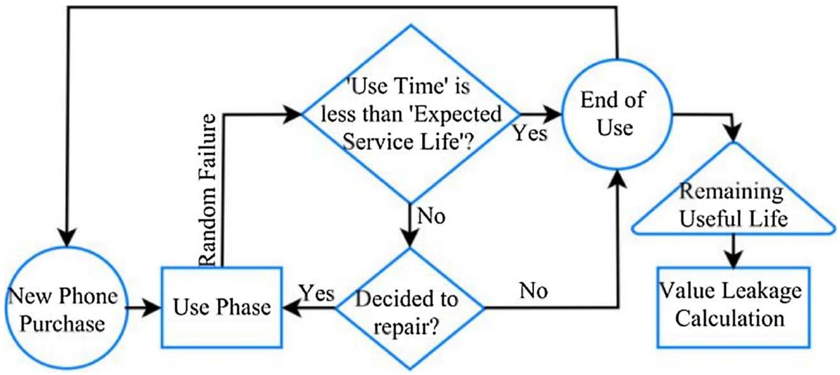

Fig. 3. The flowchart shows how the value leakage is characterized by considering consumers' repair behavior.

cycle of ownership. However, values retained from resale and reuse of mobile phones can be also measured for the next step of this study, although original manufactures may not benefit from those practices.

Another example can be assessing the relationship between economic, social and environmental values that are invoked when unwanted mobile phones are exported to developing regions. Due to the current informal recycling infrastructure in those regions, social and environmental issues may arise although there will be economic gains for local communities.

6. Value leakage characterization

In this section, the process to characterize the value leakage at the EoU time of mobile phones is discussed in three subsections. According to the flowchart depicted in Fig. 3, mobile phones would be at their EoU time in two cases: 1) their use phase exceeds the consumers' expectations for the service life of phones no matter whether phones are still functional or not, and 2) consumers decide to not repair broken phones even if phones' age is less than consumers' expected service life. The second decision, specifically, is affected by manufacturers' strategies for managing repair services. Hence, in Section 6.1, we explore consumers' attitudes towards repairing broken mobile phones. Section 6.2 is devoted to investigating strategies adopted by manufacturers. Finally, an analytical approach is developed to estimate the probability of not repairing a broken mobile phone, and consequently, calculate the total expected value leakage that may occur.

6.1. Exploration of consumer's repair attitude

How long do consumers most likely use a mobile phone? What attitudes do consumers hold towards repairing broken phones? Answering such questions is essential to capture the uncertainty in consumers' post-purchase behaviors. In fact, perhaps the most puzzling aspect is how to capture the uncertainty of the time in which these phones reach their EoU/L phases. To capture such behaviors, 208 students participated in a questionnaire with 6 questions. The number of questions was decided based on the scope of the study, and to help us estimate the parameters of the model. All students attended a decision-making system design course at the University at Buffalo. College students have been selected as the sample of younger generations who interact with smartphones more often and have a tendency to use the most recent technology while due to their economic situation may consider repair decisions as well. We acknowledge that the sample size is small, but the main focus of this study is on developing the concept of value leakage than providing an accurate estimation. More robust findings can be obtained by collecting data from different demographic groups. The survey questions and respondents responses are summarized in Table 1.

Nowadays, the average use time of a mobile phone is estimated to be less than 2 years (Umair et al., 2015). However, it might be different

Table 1
The summary of survey questions and results.

Survey Questions	Responses	Magnitude
1. How long have you been using your current cell phone?	Mean age of the phones (SD) (years)	1.7 (0.83)
2. How much did you pay to purchase it?	Mean price of the phones (SD) (US$)	473.7 (260.3)
3. How frequently do you buy a new cell phone?	Mean expected service life (SD)	2.8 (1.1)
4. Imagine a situation that your current cell phone is no longer working and needs to be repaired. You have decided to repair it. However, you have no idea how much it costs to repair it. What is the maximum amount of money that you are willing to pay to get your cell phone repaired?	Mean willingness-to-pay for repair services (SD) (US$)	129 (97.3)
5. What is the brand of your current cell phone?	Number of different brands reported by the respondents	12
6. What is the model of your current cell phone?	Mean number of different models from a brand reported by the respondents (SD)	4.4 (4.1)

from consumers' expectations about the service life of a phone (the time interval that the phone is expected to be used). To estimate the expected service life of a mobile phone (L), the students responded to the following question: 'How often do they intend to buy a new phone?' Fig. 4 shows the distribution of the responses. A log-normal distribution with mean 2.84 years and variance 1.18 years is fitted to the data. The expected service life might be different in different countries and demographic regions. For example, surveying a sample of Brazilian consumers revealed that 5.3 years was expected for the service life of mobile phones (Echegaray, 2016).

According to a report by Consumer Technology Association,[1] 183 million units of mobile phones are predicted to be sold in the U.S. market in 2016. Therefore, given the total unit sales, we can project the predicted amount of EoU/L mobile phones generated over time (Fig. 5), in respect to the point that the consumer's expectation for the service life is represented by the fitted log-normal distribution. As seen in Fig. 4, almost all the phones sold in 2016 will be out of use by 2022. But, in this case, we do not consider the fact that many mobile phones are retired sooner than consumers' expected service life spans due to the existing barriers to get the repair services.

[1] Source: Evolving Mobile Device Lifecycle Creates New Market Opportunities, Says CTA, The Consumer Technology Association, https://www.cta.tech/News/Press-Releases/2016/September/Evolving-Mobile-Device-Lifecycle-Creates-New-Marke.aspx

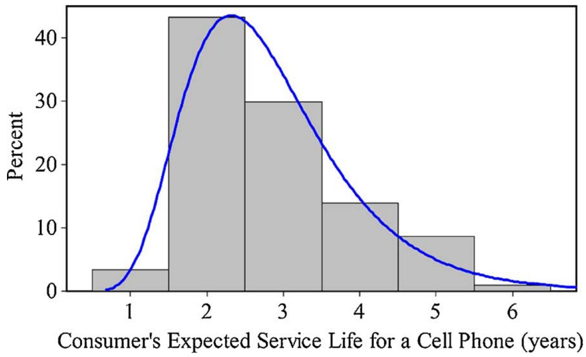

Fig. 4. The histogram of consumer's expected service life for a cell.

A survey conducted by iFixit.com in 2013 identified that the repairability and repair cost of a product entirely matter to 36.2% and 29.6% of all respondents, respectively (Sabbaghi et al., 2016). So, if repair services are accessible and fairly priced, consumers are likely to opt for repairing their broken devices. However, in practice, tons of mobile phones are left unrepaired due to costly repair services (Bollinger et al., 2012).

In order to understand the consumers' repair behaviors, the consumer' willingness-to-pay for the repair services (W) is linked to the price that a consumer paid to buy a mobile phone (P) and the age of the phone (T) extracted from the survey. Here, by price we mean the absolute purchase price of unlocked mobile phones produced by big brands and offered by almost any mobile carriers in the market (Laugesen and Yuan, 2010). Also, this is the purchase price of new technology coming to the market, not the same technology several years later. The price of a phone can be possibly bundled with that of career services, but it does not mean that the phone is provided free to consumers. In this case, the price of a phone is already included in the final price of services.

It should also be noted that the consumer repair decision is not at the time of upgrading the old phone but it is during the use phase, when a failure happens and most of the time the phone is not eligible for upgrade or discount offers. An accidental failure can happen at any time during the phone life cycle. This kind of physical damages on mobile phones are not covered by warranty according to the policy of most mobile phone carriers unless a protection insurance is purchased. Hence, consumers have to either repair or purchase a new phone.

Fig. 6 shows the distributions of the purchase price and consumers' willingness-to-pay based on the product age. It should be noted that the distribution of price is a mix of two distributions since there are two major vendors of the mobile phones with a significant difference in their selling prices. In addition, some bars do not include all range of phone age values because of the respondents' answers.

To better represent the relationship between willingness-to-pay for repair services W, price P, and age T, a new variable $R_{W/P}(t)$ named the relative willingness-to-pay is defined as the ratio of W to P at time T.

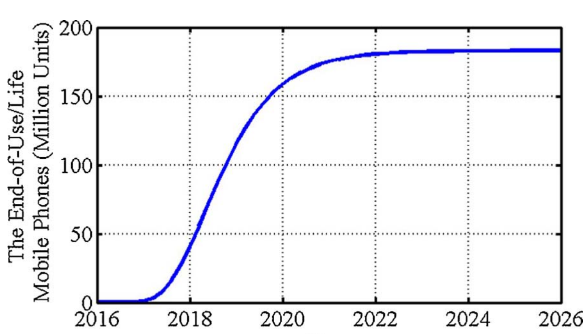

Fig. 5. The cumulative amount of End-of-Use/Life cell phones that are sold in 2016 based on the distribution of the consumer's expected service life for a mobile phone.

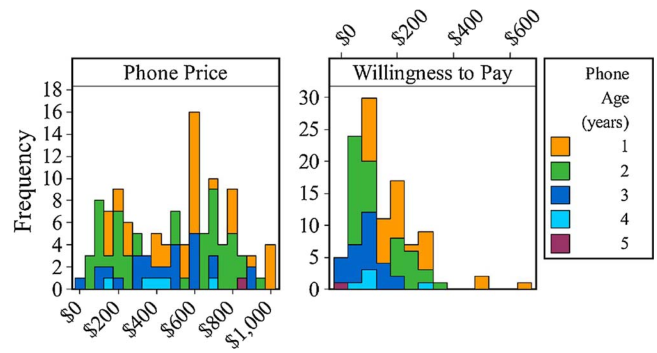

Fig. 6. The distributions of the phones' prices (P) and the consumers' willingness-to-pay for the repair services (W) based on the age (usage time) of the phones (T).

Fig. 7 represents the distributions of $R_{W/P}(t)$ for mobile phones with different ages. The distributions for 1-year, 2-year, and 3-year old phones are obtained by separating the respondents' answers. The rest of distributions are derived based on the linear relationships between the location and scale parameters of the empirically-derived distributions of the phones with age 1, 2, and 3 years. The mean of distributions decreases from 0.3504 for a 1-year old phone to 0.023 for a six-year-old phone. In addition, the distribution of $R_{W/P}(t)$ is concentrated on a single point as the age of phone increases. It means that consumers may have the same relative willingness-to-pay for repairing an old-enough phone, which converges to zero percentage of the price.

In our dataset, 12 different brands have been totally reported by the respondents, however, the two most frequently-reported brands account for 81% of the total responses. In Fig. 8, the confidence intervals are presented for these two main vendors of the mobile phones in the market. The results show that the students have the same relative

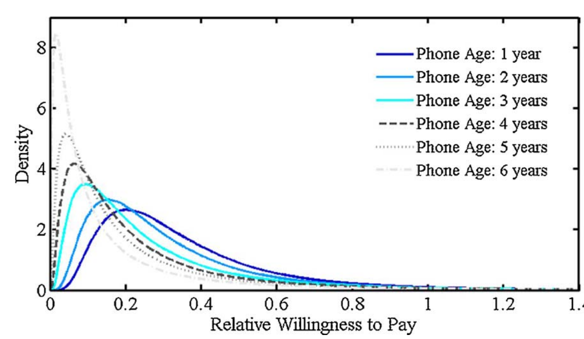

Fig. 7. The distributions for the consumers' relative willingness-to-pay based on the age (usage time) of the phones.

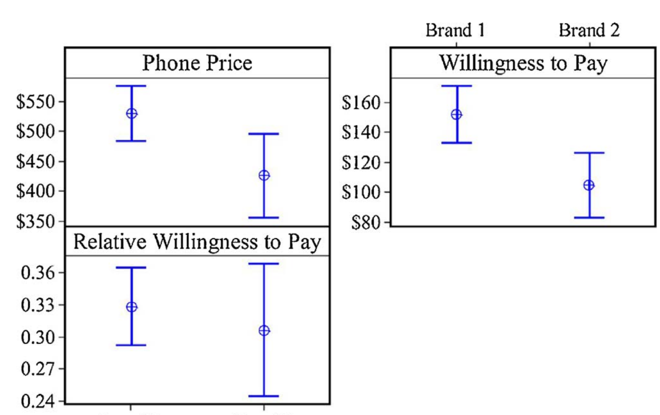

Fig. 8. The 95% confidence intervals for the phone price, willingness-to-pay, and the relative willingness-to-pay.

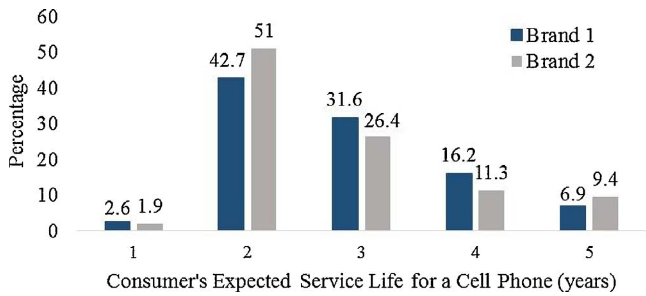

Fig. 9. The distribution of the consumer's expected service life for a cell phone manufactured by either Brand 1 or 2.

willingness-to-pay for both brands' repair services (p-value = 0.523), although the willingness to pay is significantly different for the two groups (p-value = 0.004). Therefore, we conclude that the type of brand does not have a significant impact on the consumer's relative willingness-to-pay for repair services.

Fig. 9 demonstrates the consumer's expected service life for a mobile phone offered by either Brand '1′ or '2′. The type of brand, however, is not significantly related to the consumer's expectation for the service life of a mobile phone (p-value = 0.761). Therefore, there is no heterogeneity of repair attitudes in different groups of respondents, and consumers' willingness-to-pay for repair services can be profiled regardless of brands.

To summarize this section, we discussed the collected data on two variables with the aim of capturing consumers' attitudes towards repair/replacement decisions:

1 The time that a consumer perceives their mobile phone is technologically-obsolete regardless of whether it works well or not.
2 The time that a consumer perceives their mobile phone is physically-obsolete regardless of whether it is still technologically-plausible or not.

6.2. Product design and post-sale services

The idea of extending the life span of products through facilitating repair services and increasing the repairability of products may not be acceptable to manufacturers since it may limit their sales. To survive in the competitive markets, manufacturers often have to encourage consumers to purchase new mobile phones by offering sales promotions, and pay insufficient attention to repair services. The question then arises as 'what would be the negative consequences of such policies for both manufacturers and consumers?'

In this section, we explore the provision of repair services in order to build an empirical model that describes the time-evolution of repair costs. Later on, this model will be combined with consumers' repair behaviors to quantify the risk of mobile phones' underuse.

First, let us discuss the data collected for analyzing the cost of repair services. The repair costs are not covered by warranties in two main cases: i) the product is no longer in the warranty period, and ii) the damage is not included in the warranty terms and conditions (e.g., liquid damage). Therefore, the device owner is responsible for all repair service fees if decides to repair. Table 2 summarizes the fees for three main repair services – including liquid damage, screen repair, and battery replacement. The data are collected from the official website of one of the two major brands discussed in Section 6.1. This information is not officially provided by the other brand in details. In addition to the service fees, the time that the model was released to the market (the technology age), and the to-date prices of the phones, and price of the phones at their release dates are also provided.

An overview of the data reveals that the manufacturer's strategy for the repair services is more focused on offering service for newly released products than older models. The repair services are no longer

Table 2
The repair service information for the smartphones produced by one of the two major brands discussed in Section 6.1.
(Source: vendor website).

Model Code	Technology Age (years)	Price at the Release Date	To-date Price	Liquid Damage Repair Cost	Screen Repair Cost	Battery Repair Cost
1	6.67	$749	$140	$149	*	$79
2	5.42	$849	$188	$199	*	$79
3	4.42	$849	$225	$269	$129	$79
4	3.42	$849	$293	$269	$129	$79
5	3.42	$849	$356	$269	$129	$79
6	2.42	$849	$599	$299	$109	$79
7	2.42	$949	$659	$329	$129	$79
8	1.42	$849	$649	$299	$129	$79
9	1.42	$949	$791	$329	$149	$79

*The service is no longer available.

offered for older models and in some cases, consumers have to pay considerable service fees relative to the current values (to-date prices) of their products. According to the current data, the relative repair cost of a product $R_{C/P}(t)$ could be linearly correlated to its release date.

Consider C as the repair cost, P as the purchase price of the phone at their release date, and t as the release time (e.g. the time that the model is introduced in the market for the first time). Eq. (1) represents the linear regression model for the relative repair cost of m models of mobile phones produced by a specific brand:

$$R_{C/P}(t) = \alpha + \beta t, \tag{1}$$

The parameters of the regression model are then estimated using the sets of repair data. Employing the data in Table 2, a linear model has been fitted linking the relative repair cost of liquid damage and time with R^2 of 85.5% (Eq. (2)). However, it seems that the relative repair cost of screen and battery have almost been constant over time (15% and 9%, respectively). Generally, it has been reported that the average repair cost of a mobile phone is about 26% of its original price (Proske et al., 2016).

$$R_{C/P}(t) = 0.41 - 0.03t, \tag{2}$$

We have compared the repair cost and the purchase price of the phones at their release dates. These ratios could be different if the to-date price of phones is used instead. For example, as seen in Table 2, the liquid damage repair cost for the phones aged 4.42 years and older is about their to-date price. It is more cost effective to repair a product newly released to the market than older models due to the inventory cost of spare parts (Liu et al., 2014). Recent advances in manufacturing technology may make repair activities more appealing to both manufacturers and consumers. For example, 3D printing technology can be employed anywhere and anytime to create a single part that reduces holding inventory costs (Park, 2017).

It should be noted that manufacturers have their own concerns. To remain competitive in the market, they have to offer new generations of products, where ensuring the availability of spare parts for all these products increases their supply chain costs significantly (Kissling et al., 2013).

6.3. Value leakage quantification

The value leakage quantification can be carried out from different points of view: the ineffective use of resources; the excess cost of early replacement decision imposed on consumers; and the lost opportunity of not capturing repair demand for the manufacturer.

A probabilistic approach is proposed to calculate the probability that a consumer would decide whether to repair a broken phone or replace it with a new one. Eqs. (3) and (4) represent the joint probability density function (f) for the case of repair and replacement decisions at time t over the service life l. For example, the joint probability that a consumer would like to use a mobile phone up to 3 years but s/he replaces it with a new one in case of failure over the first year of use can be calculated by using f. In both right-hand sides of Eqs. (3) and (4), a conditional distribution of decision (h) at time t given the service life equals l is multiplied by the marginal distribution (g) for the service life L.

$$f_{T,L}^{Repair}(t,\, l) = h_{T|L}^{Repair}(t|l) \times g_L(l), \tag{3}$$

$$f_{T,L}^{Replacement}(t,\, l) = h_{T|L}^{Replacement}(t|l) \times g_L(l), \tag{4}$$

Now, we can drive the probability of repair or replacement represented by Eqs. (5) and (6). Assume that a consumer decides to use a mobile phone no longer than l years. Suppose that a failure is identified in the time interval $[0,t]$, where $t \le l$, however, the consumer's decision is made at time t by comparing his/her relative willingness-to-pay for repair with the offered relative cost of repair. The consumer's decision could be to repair if s/he had enough willingness-to-pay for repair services. Therefore, according to the chain rule of probability, the probability to repair a broken mobile phone (p^{Repair}) at time t over service life l can be calculated (Eq. (5)). In addition, the probability to replace the same mobile phone ($p^{Replacement}$) is defined by Eq. (6) (complement of probability to repair).

$$p_{T,L}^{Repair}(t,\, l) = p\left(R_{\frac{W}{P}}(t) \ge R_{\frac{C}{P}}(t) \,\middle|\, 0 \le t \le L,\, L \le l\right) \times p(L \le l), \tag{5}$$

$$p_{T,L}^{Replacement}(t,\, l) = 1 - p_{T,L}^{Repair}(t,\, l), \tag{6}$$

Fig. 10 provides an example of this step of the proposed approach. In this figure, it is assumed that L is 5 years which is much higher than the average service life for a mobile phone. Furthermore, three cases of failures are considered: depleted battery, broken screen, and liquid-damaged. As seen, the probability to repair decreases for all cases of failures as the usage time (mobile age) increases. As expected, the decrease in repair probability over time is remarkable since consumers' willingness to pay for repair services decreases, while perceiving a higher relative cost of repair. In Fig. 11, the effect of service life on the probability to repair is studied. The probability to repair remarkably decreases as the consumer's expected service life decreases.

The second step is to measure the risk of value leakage by considering the value of leakage and probability of leakage for the above-mentioned leakage forms (Eq. (7)). Here, the risk of value leakage is defined as the expected losses associated with not repairing broken mobile phones. For example, assume that the probability of a mobile phone's failure over the first year of use is 0.5. Also, the probability that its owner decides to replace it although wanted to use it for 2 years is assumed 0.8. If the net cost of replacement compared to repair is \$400, the risk of monetary value leakage is 0.5 × 0.8 × \$400, \$160. Also, the risk of the phone underuse is 0.5 × 0.8 × 1(year), 0.4 year.

$$Leakage\ Risk = Value\ of Leakage \times Probability\ of Leakage, \tag{7}$$

The leakage risk of a mobile phone's underuse (LRP) is given by Eq. (8). Suppose that a consumer decides to replace a broken mobile phone at time t. Then, the expected remaining service life is l-t, which in fact is the amount of time that the consumer can use the mobile phone if it is

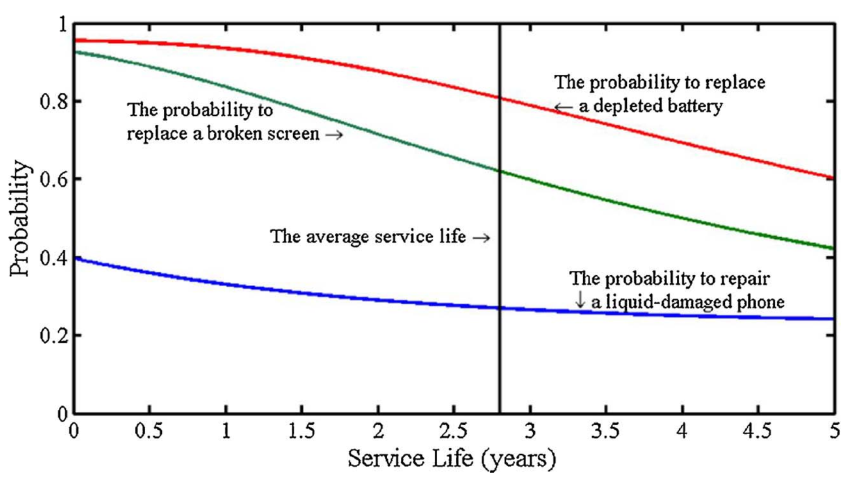

Fig. 10. The probabilities to repair a phone with depleted battery, broken screen, or liquid damage issues over the phone's service life (L = 5 years).

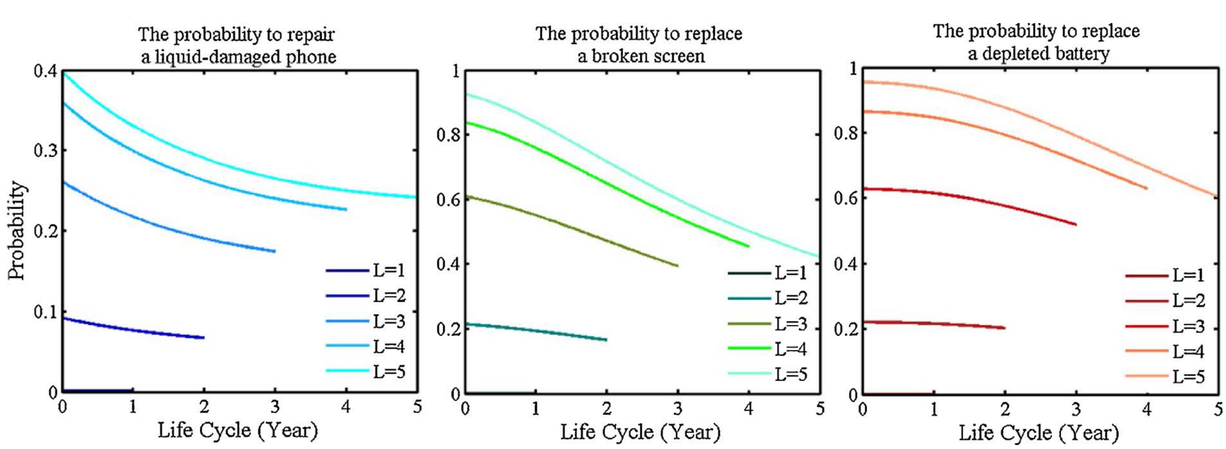

Fig. 11. The probability to repair with the depleted battery, broken screen, or liquid damage issues for different values of expected service life.

being repaired. We also need to determine how likely it is that a value leakage case occurs. The probability of replacement decision ($p^{Replacement}$) is given by Eq. (6). It is assumed that α% of consumers may experience a specific failure like a broken screen over the usage phase of their mobile phones. On the other hand, failures occur uniformly during time period [0,*t*]. Thus, the probability of observing a failure (*p (Failure)*) in time period t can be quantified as Eq. (9).

$$LRP = (l - t) \times p_{T,L}^{Replacement}(t, l) \times p(Failure\ in\ time\ period\ t), \tag{8}$$

$$p(Failure\ in\ time\ period\ t) = \alpha \frac{t}{l}, \tag{9}$$

In a similar way, the leakage risk for a consumer and a manufacturer can be quantified. For the case of replacement decision, a consumer purchases a new phone with price P_{New} and sells his/her old broken mobile for *S*. The monetary value of leakage for this person is then P_{New}-$C(t)$-S, where $C(t)$ is the repair cost at time *t*. Here, it is assumed that a repaired mobile phone is as good as new one. Thus, the difference between the expected lifetime of a new and repaired phone is not significant. In addition, the new phone is likely to be more technologically-advanced that affects consumers' replacement decisions. However, it is difficult to ascribe a monetary value to the perceived technology valuation.

In this situation, the monetary value of leakage for the original manufacturer is the amount of profit (*Π*) from doing repair services. Consumers may or may not switch between brands, however, in this model, it is assumed that most of the consumers do not stay with the same brand if they decide to replace the old phone. This is not an unrealistic assumption, as surveying consumers has shown that repairability of a product influences their loyalty (Sabbaghi et al., 2016). Eqs. (10) and (11) demonstrate the leakage risk for a consumer (*LRC*) and a manufacturer (LRM), respectively.

$$LRC = (P_{New} - C(t) - S) \times p_{T,L}^{Replacement}(t, l) \times p(Failure\ in\ time\ period\ t), \tag{10}$$

$$LRM = \Pi \times p_{T,L}^{Replacement}(t, l) \times p(Failure\ in\ time\ period\ t), \tag{11}$$

What would be the total expected leakage risk for a population size of *M*? Assume that *M* million units of mobile phones are being sold by a manufacturer over a year. Buyers of these phones have a different expectation for the service life (Fig. 9). Thus, we define m_l as the number of consumers who expect to use their mobile phones for *l* years. Also, $E_l(.)$ represents the expected leakage risk for service life *l*. Then, the total expected leakage risk *TE(.)* is obtained as:

$$TE(.) = \int_{\infty}^{l=0} E_l(.) m_l dl, \tag{12}$$

For the purpose of illustration, the approach is applied to an example of repairing damaged-screen phones manufactured by Brand '1'. The US market share of this brand is about 42%. Therefore, given that 183 million units of mobile phones have been sold over 2016 in the US, 76.86 million units are manufactured by Brand '1'. From Fig. 9, the values of m_l can be obtained by multiplying the percentages of respondents with expected service life *l* to 76.86 million units.

According to a survey study, a damaged screen has been experienced by 34% of mobile phones users in the U.S.[2] This value is an estimation of α in this example. We assume that the new mobile phones and the old ones would be in the same price range. Thus, the price of a new phone P_{New} is estimated to be the average price of the previous models released by Brand '1'. The salvage value of the old broken mobile *S* is about \$85. This value is found from the website of a used electronics trade-in program. Finally, a 30% is assumed as the average gross profit margin of mobile phone repair services. There is no accurate published data on the profitability of repair services, however, the average gross profit of 3887 companies – including consumer goods – was estimated 46% in 2007, where most of the companies had a gross profit margin more than 30% (Kemmerer and Lu, 2012) In other words, *Π* is 30% of the total repair cost *C(t)* offered by Brand '1'.

Table 3
Leakage risk quantification for a case of damaged screen repair.

l (years)	t (years)	LRP (years)	LRC (US \$)	LRM (US \$)	m_l (million units)
1	0	0	0	0	0.026 × 0.42 × 183
	0.25	0.064	54.69	3.28	
	0.5	0.085	109.40	6.55	
	0.75	0.064	164.12	9.83	
	1	0	219.16	13.11	
$E_{l=1}(.)\rightarrow$		0.042	109.41	6.55	
2	0	0	0	0	0.427 × 0.42 × 183
	0.5	0.1	43.38	2.6	
	1	0.137	88.6	5.31	
	1.5	0.105	135.16	8.1	
	2	0	183.35	11	
$E_{l=2}(.)\rightarrow$		0.068	90.1	5.4	
3	0	0	0	0	0.316 × 0.42 × 183
	0.75	0.083	23.73	1.42	
	1.5	0.125	53.71	3.22	
	2.25	0.105	90.57	5.43	
	3	0	133.23	8	
$E_{l=3}(.)\rightarrow$		0.063	60.25	3.61	
4	0	0	0	0	0.162 × 0.42 × 183
	1	0.062	13.32	0.8	
	2	0.12	38.69	2.32	
	3	0.117	75.48	4.52	
	4	0	120.19	7.2	
$E_{l=4}(.)\rightarrow$		0.06	49.53	2.97	
5	0	0	0	0	0.069 × 0.42 × 183
	1.25	0.061	10.57	0.63	
	2.5	0.147	37.89	2.27	
	3.75	0.152	78.62	4.71	
	5	0	127.02	7.60	
$E_{l=5}(.)\rightarrow$		0.072	50.82	3.04	
$TE(.)\rightarrow$		4,976,000	5,525,000,000	331,000,000	

Table 3 summarizes the findings, which determined that the total expected leakage risk for the mobile phones is about 4.98 million years based on consumers' expected service life. It means that the mobile phones were probably underutilized. The consumers were likely to spend 5525 million dollars to purchase new mobile phones, and the manufacturer loses an expected profit of about 331 million dollars.

A sensitivity analysis is carried out to show the effect of a parameter such as the frequency of screen damage (α) on the expected leakage risks (Fig. 12). In this figure, the Time Leakage Risk refers to the total expected amount of time that mobile phones could be potentially used,

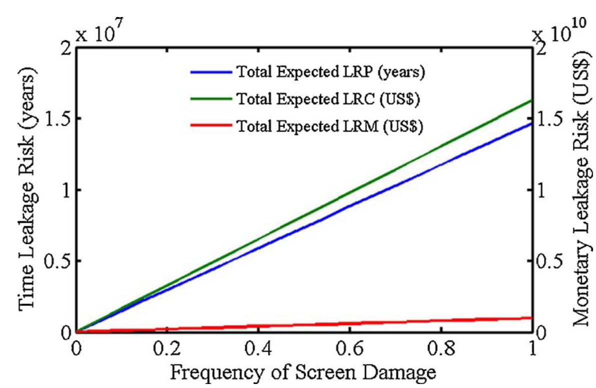

Fig. 12. The changes in value of time and monetary leakage risk based on the frequency of screen damage.

[2] Source: Cracked Screens and Broken Hearts: The 2015 Motorola Global Shattered Screen Survey, The official Motorola blog, http://motorola-blog.blogspot.com/2015/10/cracked-screens-and-broken-hearts-2015.html

but are not due to consumers' not-to-repair decisions. Both time and monetary leakage risks increase significantly as the frequency of screen damage increases. It should be noted that the value of α is related to usage behaviors of consumers and the quality of phones' design.

7. Discussion and closure

In this paper, the concept of value leakage has been introduced, and expected losses that may occur due to consumers' decisions to not repair broken devices has been quantified. A probabilistic approach has been developed to calculate the total expected leakage risk indicators *TE(LRP)*, *TE(LRC)*, and *TE(LRM)*. It has been shown that consumers expect to use mobile phones for 2.8 years on average, although they have willingness-to-pay for repair services throughout the life span. We also found that consumers' willingness-to-pay for repair services decreases at an annual rate of 6.7% during the use phase of their mobile phones. Thus, it seems that consumers have relatively robust repair behaviors, however, costly repair services offered by manufacturers may dissuade them from repairing broken devices. As a result, consumers may dispose of broken devices, which results in the value loss for both consumers and manufacturers.

For the case of damaged-screen phones, it has been shown that a manufacturer may lose up to 331 million dollars since the replacement cost of a screen is perceived to be relatively high compared to the purchase price by consumers. On the other hand, new mobile phones are probably purchased by consumers, which cost them about 5.5 billion dollars. It should be noted that we assumed that all consumers will shift to a different brand if they decide to purchase a new device. However, this value can be easily adjusted by the percentage of consumers who may stay with the same brand despite experiencing failed products and no repair decision. From the resource consumption perspective, discarded mobile phones are underutilized, which is another type of value leakage.

In this study, the findings may be biased with the point that the sample of consumers who participated in the survey mainly used big brands of cellphones. There are many manufacturers of non-branded low-cost mobile phones around the world that do not emphasize on brand names as much as the big brands do. On the other hand, instead of promoting repair services, big brands adopt other marketing strategies (i.e., offering trade-in rebate) to foster brand loyalty, thereby decreasing phones longevity. It simply means that phones repair may not be of concern for manufacturers. However, corporates have also other concerns (e.g., social and environmental responsibility, and material scarcity) that underpin the promotion of phones repair services. In this paper, we aimed to show the economic benefits of promoting repair services for manufacturers, although products' ease-of-repair must be upheld as a consumer certain right.

The current study is limited to students' opinions and lacks the information on the attitudes of other groups of consumers. In addition, the repair cost is not the only factor that affects consumers' willingness-to-pay for repair services. The impact of other socio-demographic factors such as income and education level should be studied to better explain attitudes.

The current study can be extended in several ways. The total expected leakage has been investigated only for the case of damaged-screen mobile phones produced by only one manufacturer. The total value leakage may be much larger if we consider all types of consumer electronics and all modes of failures.

The leakage risk indicators *LRP*, *LRC* and *LRM* can be used to measure the sustainability performance of a product consumption. These indicators should ideally be zero, however, this perfect equilibrium state cannot be easily achieved in practice. Lower-level equilibrium states can be attained when repair services are being facilitated by manufacturers, and sustainable behaviors are being fostered in consumers as much as possible.

The developed methodology to capture the value leakage of unrepaired mobile phones can be extended to include the case that the price of phone is bundled with the cost of career services. In this situation, consumers receive a substantially discounted or free mobile phone at the time of acquisition. To extend the model, additional parameters such as consumers' willingness-to-pay for upgrade and the remaining time to contract expiration should be considered.

The estimated flow of EoU/L mobile phones shows that a significant proportion of unwanted mobile phones end up in landfills, are incinerated, or exported to developing countries. The environmental damages associated with these improper recovery activities can be counted as another type of value leakage. Quantifying this 'environmental leakage' is another line for future research. In addition, we have found that consumers have less propensity to repair an older phone. Many failed products are still technologically innovative, but the main impediment to repair them is the cost of repair. So, consumers should be encouraged to take them back to manufacturers or certified recyclers for the material extraction or second-hand reuse, preventing further value leakage and environmental damages. However, it should be noticed that repairable products are less likely to be sent to remanufacturers by consumers since they can easily repair them in the first life cycle.

Another area for future study is to include other stakeholders in conceptualizing the value leakage. For example, the unemployment rate of private-sector repair technicians can be employed to evaluate value losses from the social aspect. Public authorities and cooperatives can also be considered as a stakeholder, who attempt to design environmental policies and evaluate the corresponding impacts.

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