CLOUD BASED SENSOR ANALYSIS FOR CUSTOMER-SPECIFIC RESIDUAL VALUE ESTIMATION FOR END-OF-LIFE PRODUCT RECOVERY

BY

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THESIS

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Abstract

Manufacturing companies that take back products at the End-Of-Life (EOL) face a decision whether to recycle, remanufacture, repair, refurbish or scrap that product. One of the first steps is to estimate the product's residual value, primarily on the basis of age and a cursory visual inspection. However, there is a high degree of variability in actual value, even for products of the same age. This is due to the variability of environmental and use conditions to which the product has been exposed by the consumer. This paper proposes a predictive model that uses data obtained from sensors which is stored on the cloud, throughout a product's lifecycle. This data is used to more accurately estimate the value at the EOL. The model recommends the EOL solution for an individual product based on the quality level and demand for refurbished products. An illustrative cell phone example is presented, which tracks the condition of each phone during its lifecycle. Simulation is performed to obtain the residual value distribution based on predictive indicators from sensors including accelerometer data to monitor number of free falls and impact, number of battery lifecycles, humidity and temperature sensors. Results indicate improved residual value estimation due to minimizing the loss due to variance in quality of products.

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1. Introduction

Manufacturing companies look to refurbish or remanufacture products in order to reduce environmental impact, recover value, comply with government regulation and get additional revenue through sale of refurbished products. However, End-of-Life (EOL) product recovery, refurbishing and resale is difficult because of the high degree of variability in quantity, quality and timing of returned products. Refurbishing facilities have to inspect, sort and then disassemble every product before replacing components and refurbishing products to meet the quality specifications, increasing the costs and complexity which often makes it unprofitable to remanufacture. This high variability and lack of information is the reason the entire process is highly inefficient.

End-of life product recovery can be profitable, creating a circular economy [1]. But take-back and remanufacturing operations are complex, and for some products, profitability is low. “Smart”, connected products offer tremendous opportunity for transforming the business model towards better products and greater profitability for a broad range of businesses [2]. Product take-back and remanufacturing is one of them. For example, information can be obtained from a “smart” product and communicated to the manufacturer. The manufacturer then has information about the product, which can then be used in a variety of ways to make take-back and remanufacturing operations more cost-effective. For example, information on the product from the Original Equipment Manufacturer (OEM) can be combined with service interval data to be used as part of a cloud based remanufacturing solution [3] and provide the refurbishing facility with information about the components that need replacement, along with the bill of material (BOM), product disassembly sequence and quality testing process.

A body of work has analyzed both the engineering and economic issues involved in product take-back, and only a small sampling is discussed here. It includes design that anticipates product take-back [4] including data mining methods [5], managing the product return process [6] and considering multiple stakeholders [7]. The remanufacturing process typically begins with the crucial step of estimating the condition and residual value of end-of-life products when they are brought to the remanufacturer. This is done primarily on the basis of their age or effective age [8], model, and a cursory physical inspection of the product [9]. Part of what makes cost-effective remanufacturing difficult is the wide variability in the incoming feedstock of used products, especially in terms of quality. The causes of this variability are that customers return them for remanufacturing at different ages, ranging from a few months to many years, and that individual customers subject their products to a wide range of conditions.

Manufacturers have had little or no data on the conditions that each individual product experienced during the consumer-use phase. Thus, both OEM's and third party recycling and refurbishing companies deal with a high degree of uncertainty on the quantity, quality and timing of the return. While research has been done to minimize the negative impact of uncertainty in quantity of product received [10] or lifecycle uncertainty [11] little attention has been given to the range of uncertainty in the overall product quality that is a primary determinant of residual value due to lack of information on that particular product. The need to deviate from a "one size fits all" was addressed in [12], but that approach simply breaks the market into segments, rather than individual products.

The potential market for refurbished products is significant; it is estimated that market for refurbished cell phones will reach 120 million units by 2017 [13]. However, many nations have laws that prevent un-refurbished waste products from being imported so as to prevent accumulation of e-waste and prevent hazardous unregulated recycling operations. As a result, refurbishment operations must be conducted in locations with higher labor costs, prior to export of the refurbished product. Thus, there is a need to identify which individual products can undergo these expensive operations profitably so that this developing market economy can be served.

Manufacturing companies and third party firms have to invest time and resources to transport, inspect and sort products and then decide whether it is profitable to refurbish, remanufacture, recycle or dispose. The assessment of residual value is currently being performed on the basis of information obtained only after the product has been returned. This leads to inefficiencies in the closed-loop system since every unit must be first transported, inspected and sorted. This process could be streamlined if there was more information available for each unit prior to being returned.

a. Definitions

1. Refurbishing: Refurbishing is the reprocessing of used equipment at minimum cost in order to ensure that the product performance is within the bounds of what is considered acceptable for reuse [14]
2. Remanufacturing: It is the process of disassembling used items, inspecting and reworking the components and using these in a new product manufacture [15]
3. Recycling: Recycling is the process of recovering material after a product has been discarded [14]

It is important to note here that the terms remanufacturing and refurbishing are used interchangeably in this thesis.

b. Motivation

In summary, what is needed is a method for gathering information from individual products, communicating that information and making more precise remanufacturing decisions about individual products. The section below describes a method for providing manufacturers and refurbishing firms with a better estimate of the residual value of an individual product at the EOL. This has the potential to:

- Reduce or eliminate inspection costs and in some cases even disassembly cost
- Increase the efficiency of logistics and transportation at the EOL by directly shipping each product to its ultimate destination
- Provide greater insight into consumer usage behavior that can be used for designing and marketing future products for narrower market segments
- Improve quality and reliability of refurbished market products.

The example of cell phones was selected because of its high value, high production volume, low physical volume and resulting transportation costs, growing industry, short live spans and thriving second hand market. Other industries that were considered were automobile, fashion, electronics such as computers and televisions. There are more cell phones being reused than recycled. [16]

c. Drivers

There are several drivers that might lead an electronic goods or a cell phone manufacturer to start operations in refurbishing. Usually, it a combination of two or more of the following factors:

1. Commitment to sustainability:

   Electronic manufacturing companies realize the impact of disposed products and accessories on the environment. Waste electricals and electronics is the fastest growing waste stream in the world and is expected to grow from 41.8 million tons in 2014 to 50 million tons of waste in 2018 [17]. As we have seen with other sources of waste and pollution, such as fossil fuels, it becomes harder to transform and reduce the impact of a source of pollution once the source becomes an essential part of the system. It therefore becomes vital that the electronics industry develops a system of minimal environmental impact. Many customers also expect manufacturers to commit to sustainability, which adds pressure on the companies to act towards sustainability.

2. Regulation:

   In the European Union, the Directive 2002/95/EC and then Directive 2012/19/EU [18] on Waste Electrical and Electronic Equipment (WEEE) requires manufacturers of EEE to be financially and socially responsible for products manufactured or sold by them. In the United States, several states have passed similar regulations. The state of California passed the Electronic Waste Recycling Act of 2003 that placed several limitations on the manufacturers in disposing of electronic products and also established standards for recycling fees for waste electronics. Similar acts have been passed in 25 other states as of 2015, in the U.S. Canada, Japan and China have also passed legislation which holds the OEMs directly responsible for waste electronic and electrical goods.

3. Value recovery:

   Due to limited natural resources that are needed to manufacture electronic products, OEMs have an option of reusing already processed materials and thereby saving resources, time and cost. The idea of building a product once and selling it twice has been implemented by many companies but Kodak takes this a step forward [19]. The camera manufacturing company reuses almost every component in its single use cameras, several times before parts are recycled. Other heavy engineering companies may use only certain expensive components that help them reduce production costs.

4. Protection against second hand market:

   Used electronic products such as cell phones are often sold in the second hand market, either directly or after refurbishing. The quality and reliability of these used products sold by third part refurbishing companies are often inferior compared to refurbished products sold by OEMs [20]. This leads to a diminished brand perception in the eyes of the customer. The meagre existence of refurbishing companies show that the business line is profitable and therefore OEMs seek to increase their profits by entering into the refurbished business themselves, and as a result protecting the brand image.

2. Literature Review

Since the late 1990's, researchers and policy makers realized the growing impact of Waste Electrical and Electronic Equipment (WEEE). Luk van Wassenhov and Daniel Guide have been pioneers in the field and spoke of operational challenges in their paper Managing Product Returns for Remanufacturing [19]. They spoke about whether a product acquisition management team determines if reuse is a value adding activity or not. They also discussed if it is profitable, and how to maximize revenue by selecting appropriate methods for recovery. This paper also discusses operational issues such as facility design and inventory management are dependent on the method as well as economic benefits of remanufacturing.

Guide and Srivastava [21] showed that remanufacturing activities are significantly more complex than original manufacturing activities since the raw material input in remanufacturing has a higher variability in the timing, quality and quantity of the returns. This leads to elevated costs for the firm and increases the challenges in managing the operations.

For the past two decades, significant research has been done on supply chain issues at the End of Life. Research has been performed on inventory management, product acquisition, reverse logistics and other operational challenges. Moritz Fleischmann developed a general and systematic framework for quantitative models for reverse logistics. He discusses distribution planning, inventory control and production planning as the three main areas of research. [22]

Certain challenges in the supply chain are unique to reverse supply chains at the end of product's lifecycle. The variability in quantity, quality and timing of returns is very high, which makes it hard to forecast product returns, which adds to operational costs. Refurbishing facilities deal with a variety of products and models, which makes the disassembly process more complex than assembling a new product. Thierry and Wassenhov speak about the strategic issues in product recovery in a 1995 paper [23], focusing on information acquisition while describing the issues and suggesting solutions to the various options that companies have at the EOL. The use case studies on BMW and IBM to describe industry practices.

Since the used product is the basic input of refurbishing facility, procuring the right quantity of used products at the right time can reduce inventory costs. Ostlin et al. speak about the importance of closed loop supply chains for remanufacturing. They describe seven different ways of closing the loop and procuring a product at the EOL, including buy-back, service-contracts and credit based deposits amongst others [24].

Schultmann speaks about network modeling in his paper ‘Modeling reverse logistic tasks within closed-loop supply chains’ and uses examples from the automobile industry. He uses three scenarios to show how dismantling products can be achieved with a minimum number of facilities with the aim to reduce transportations costs [25]. Fernandez et al. also speak about network design and a distribution network strategy including transfer pricing schemes for stochastic demand [26]. He considers uncertain markets, a flexible network design and investments required for the EOL operations. His contribution is to include financial issues while studying various options in the supply chain with the objective to improve post-tax, bottom line maximization.

Savaskan et al formulate an optimization model to show the best reverse channel structures from procuring used parts. They provide three options for reverse procurement and explain a centralized and decentralized channel structure [27]. Atasu and Wassenhove speak of the product take back legislation from the operations point of view. They use the interface of systems design and economic modeling to suggest e-waste take back policies and show examples from the EU, Japan and the United States [28].

'Maximizing Profits from End-of-Life and Initial Sales with Heterogeneous Consumer Demand' by Zhao and Thurston focuses on optimizing the initial sales and end of life cycle value. In this paper, a mathematical model is developed to integrate end-of-life recovery value considerations with product design decisions. A different approach to the same problem, with a process optimization approach instead of a product optimization is suggested in this thesis [29].

Research has been done by Behdad, Williams and Thurston on EOL decision making for used products with uncertain quantity of returns. They recommend a stochastic programming model for waste stream acquisition systems. They use an example of a used CPU at a refurbishing company to decide what proportion of the device should be disassembled before it ceases to remain profitable [30]. Mashhadi and Behdad speak about upgrade planning of used products while considering uncertainty in market demand, quantity and variability in quality of returns. The paper shows the best upgrade level for a returned product in order to maximize the profit by using an example of a computer [31].

Recently, research has been growing in integrating remanufacturing activities using cloud services. Jozsef Vancza and Lihui Wang [3] proposed a cloud based approach to remanufacturing and recycling for the Waste Electrical and Electronic Equipment (WEEE). Lihui Wang and Xi Wang speak of using an integrated web based manufacturing and cloud computing by bringing suppliers, OEMs, customers, collectors, refurbishing and disposing service providers, all on a single integrated platform. At the EOL, a customer can return the product and the refurbishing company automatically receives information on the product including technical specification, Bill of Materials and disassembly plans. They suggest using a

QR Code based system and also include lifecycle assessment which is integrated onto the product's cloud system at service intervals [32]. Bin Lu, Jianxin Yang and Bo Li attempt to formulate Waste Electrical and Electronic Equipment (WEEE) by jointly considering the three pillars of sustainability: environment, economy and society using Life Cycle Sustainability Assessment to measure reusability of products [33]. Rahimifard suggests a knowledge based approach and presents cases using a computer aided recycling process planner to determine the ecological impact [34].

There has been research specifically on cell phone refurbishing and recycling. Geyer and Blass speak specifically about cell phones and examine the economics of cell phone reuse and recycling based on detailed primary data [16]. They conclude that as long as the yield of use for cell phone refurbishing companies is greater than 50%, they can remain profitable. This large gap in yield rate is what this thesis aims to cover and increase the overall efficiency. They also identify that a major problem for the cell phone refurbishing industry is that many users simple do not return used phones and leave them without the device being used, which can be solved by correct incentives.

While a lot of research has been done to improve the existing system of refurbishing and recycling, with the objective of reducing operations and logistics cost, control the timing of products and even predict the quantity of returns, using the cloud to help in disassembly, very little has been done to predict the quality. The high variability in the quality of returned products is assumed while trying to solve other issues, even though this same variability in quality increases refurbishing activities. This thesis aims to better estimate EOL product quality and as a result, its value. This information can help OEMs make better decisions and improve the system's overall efficiency.

3. Methodology

This chapter describes a new methodology for estimating the residual value of a product during the customer use phase by gathering and analyzing data generated from the product via the cloud. The current system of cell phone recovery and refurbishing is highly inefficient. In this example we consider three websites, Best Buy, Amazon Returns and Gazelle, which offer services to take back cell phones based on basic information. The following images were taken from the websites on April 5th, 2016.

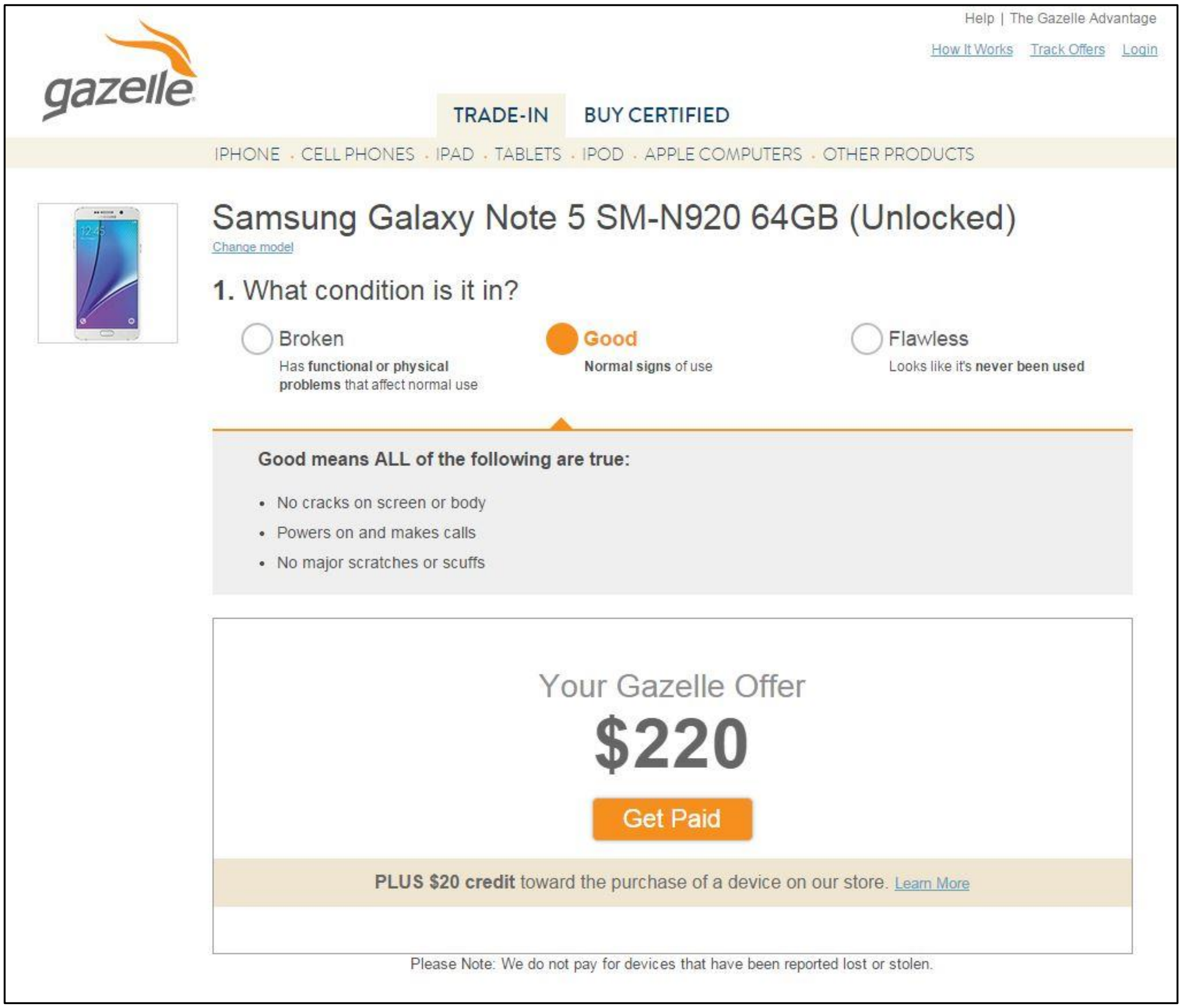

Figure 1: Example of current system of return - Gazelle

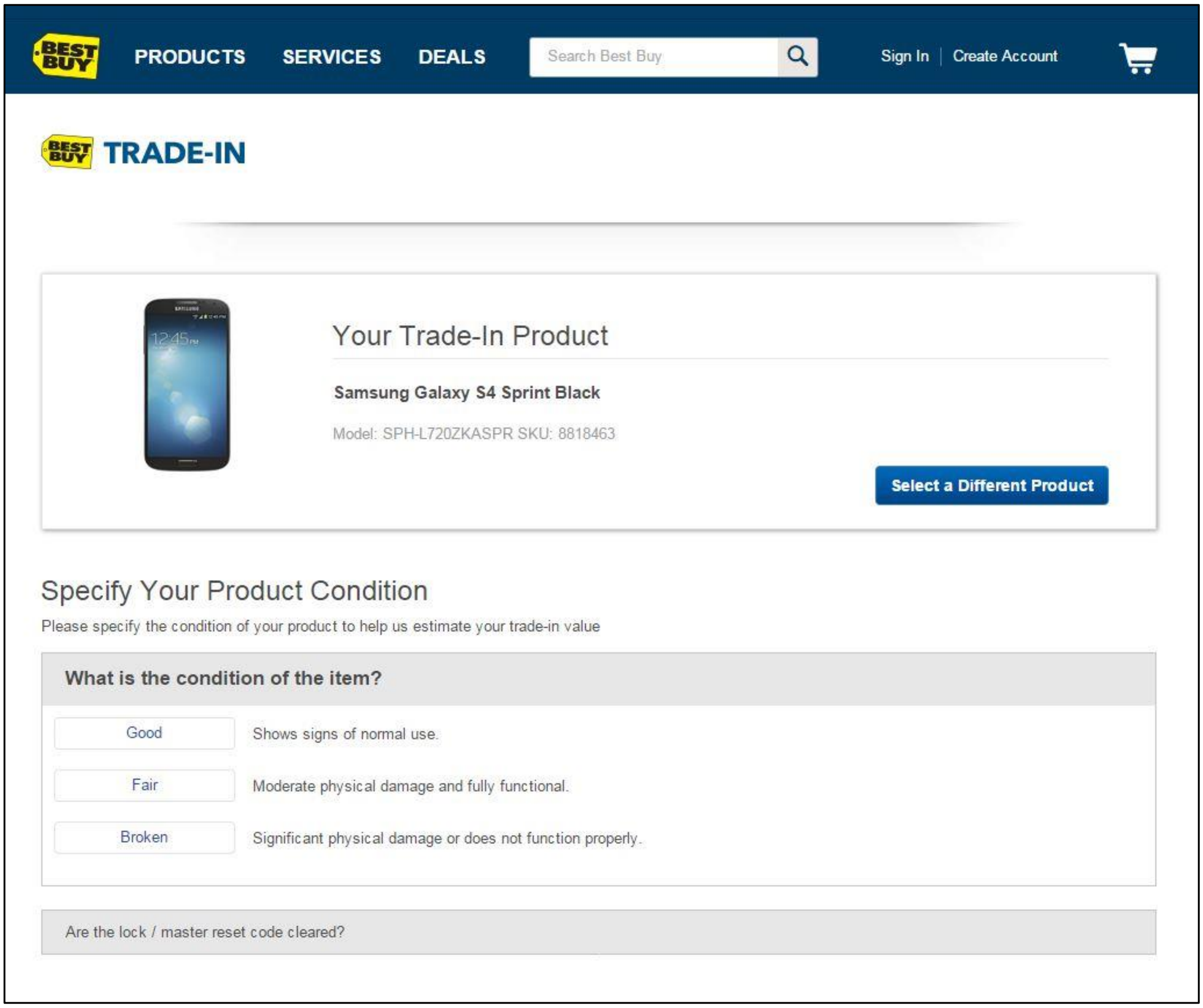

Figure 2: Example of current system of return - Best Buy

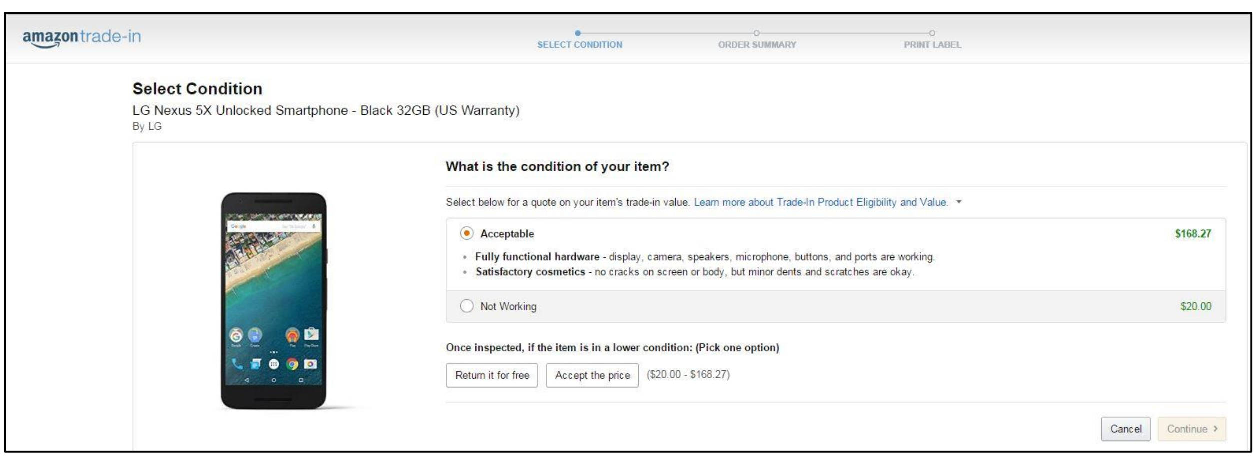

Figure 3: Example of current system of return - Amazon Trade-in

We can observe from the three websites that other than the model name and number, the only information asked is the customer's perceived condition of the cell phone. Gazell asks the customer to rate their phones either as 'Broken, Good or Flawless'. Best buy provides three options, 'Good, Fair or Broken' and Amazon simply provides the options 'Acceptable or Not Working'. After selecting the perceived condition of the cell phone, customers can proceed to receive a payment and ship their phones to the company warehouses. These companies rely on a principle of Averaging Returns, where certain cell phones will not be worth what the company has paid the customer while some will be more than the amount paid. On average, the company decides its pricing policy such that on average a certain profit margin is achieved.

The proposed methodology is shown in Figure 4. This framework for more accurate estimation of the residual value of individual products uses data obtained from sensors located on the product throughout the product's lifecycle. The raw data is logged on the device's memory and regularly updated to the cloud. The sensor data can be rewritten once the data has been uploaded. The first two stages occur on the customer's end, after which the manufacturer's or a third part's cloud storage systems stores the data until the EOL. This data is then filtered so as to reduce the data warehousing costs until it can be directly used in the analysis at the EOL.

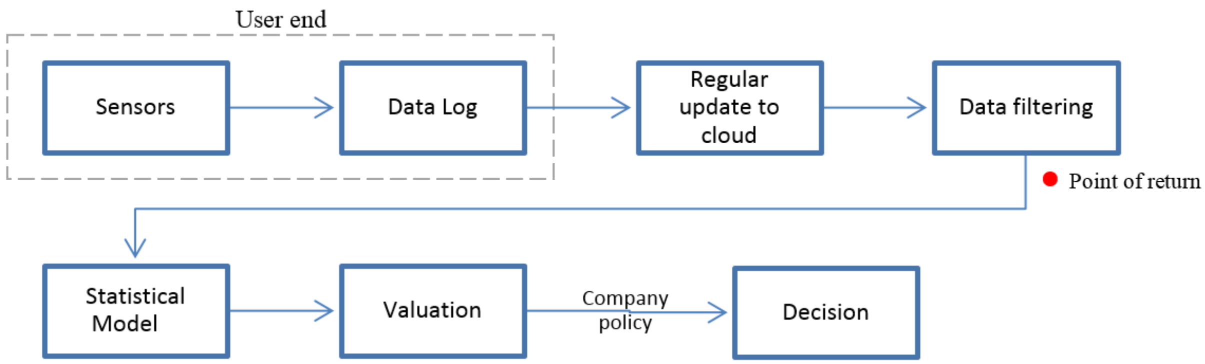

Figure 4: Cloud Based Method for Residual Value Estimation

Once the customer declares the product to be WEEE (Waste Electrical and Electronic Equipment), the product is returned through the reverse logistic channels which may include drop off points, direct shipment or product return as part of an upgrade or exchange scheme. At the point of declaring the product as WEEE, the data for that particular product is accessed from the cloud storage system, and using a pre-determined, product level valuation model, the value of the individual product is determined. The decision to be taken at an individual product level then depends on multiple market, regulatory, operational and financial factors which can be considered by the manufacturer or third party refurbishing company. Based on these factors, the product is transported to its final destination without the need for further inspection or testing. The final destination could be a refurbishing, recycling or disposal facility.

This approach can also be used to actively predict and control when a product is defined as WEEE, thereby optimizing product take-back timing. The original equipment manufacturer (OEM) can collect processed sensor data, and forecast the price and demand in both domestic and international markets. Based on the logistics, refurbishing and distribution costs of the used product, it can then determine when it is most profitable to refurbish each product, and can use this data to set take-back pricing. At this point, the manufacturer must also consider the impact of cannibalization of new product sales due to availability of lower-cost, refurbished cell phones [13]. Since manufacturers offer warranty on refurbished products and market them to be as good as new, a segment of the market would chose to buy remanufactured products due to its low price, yet good quality. Manufacturers must price both products to maximize overall profitability.

4. Application to Cell Phones

There are two advantages to obtaining information on the cell phone's quality before the EOL. Firstly, the information can eliminate the need for quality inspection and reduce transportation costs by directly transporting each product to its final destination, while enabling the manufacturer to better forecast supply for its refurbishing process. Secondly, it can help the refurbishing facility with information about the specific components needing refurbishing or replacement. This can be combined with other elements of a cloud based remanufacturing system, as described in [3].

a. Sensors, Data Log & Data Filtering

Cell phones are equipped with a variety of sensors for the purpose of safety and use in applications. Most smartphones have more than a few of the following sensors:

- Accelerometer
- Gyroscope
- Magnetometer
- Proximity sensor
- Light sensor
- Barometer
- Thermometer
- Humidity sensor
- Pedometer
- Heart Rate monitor
- Fingerprint sensor

This thesis aims to use sensor data to estimate the quality and value of a particular cell phone. The following 4 sensors were selected based on the assumption that the data that each sensor reflects has an impact on the end value of the cell phone.

- Accelerometer:

  This framework assumes that mishandled products have a reduced aesthetic value and the reliability of components is also reduced. In the case of cell phones, it is common for the device to be dropped onto hard surfaces, damaging the physical body which leads to higher costs for refurbishment and a reduced resale value. The accelerometer can be used to detect free fall and impact, therefore indicating a reduction in quality and overall value, when analyzed in conjunction with data obtained from other sensors.

  There are a various demonstrated methods to detect a free fall using either accelerometers or gyroscopes. The accelerometer measures linear acceleration, whereas a gyroscope measures angular velocity. Research has been performed on identifying free fall using these sensors to detect if an elderly citizen has fallen. A tri-axial accelerometer was used in [35] by setting thresholds to the velocity, acceleration and angle parameters, and they were able to detect free fall with a 98.9% accuracy. A biaxial gyroscope was used in [36], and they applied thresholds to peak angular velocity, angular acceleration and torso angle change of the subject and were able to detect free falls with a 100% accuracy. If only instances of free falls are detected, it might lead to an inaccurate model since it ignores the height of free fall, and impact upon free fall, both of which significantly impact the final output. In our primary example of cell phones, it is not uncommon for users to throw the device on softer surfaces. Therefore, it is important to detect the height of freefall and impact, while filtering the noise. While designing a free fall detection system for a Personal Emergency Response System

(PERS) [37], used a self-learning algorithm to collect data and improve the accuracy of detection. They also have been able to predict the different types of false-positives, including free fall on elastic surfaces, which occurs when the subject is sitting down.

- Battery:

  A cell phone's battery usage is a direct indicator of the number of hours the device has been used. Each battery is designed for a certain number of charge cycles, which are commonly between 400 to 500 cycles after which the State-of-Charge (SoC) drops and the Depth-of-Discharge rises. Battery usage has a high degree of variability as it depends on the user's charging cycles, overcharging, high voltage or amperage and total number of cycles. The total number of cycles is an indication for the expected Mean Time to Failure (MTTF) for other components in the phone as well. During the refurbishing process, the battery often needs to be replaced which lead to additional costs. Therefore, data from this sensor is significant and impacts the value of the phone at the EOL.

- Temperature:

  Temperature sensors are present only in certain brands but a growing number of manufacturers are including this sensor to find the room temperature for use in applications. Electronic components have a temperature specification, which when exceeded could decrease the reliability of the components and reduce the time to failure. Temperature specifications are approximately 32° F to 95° F, which are often violated as customers use their phones in more extreme environments. More research needs to be done on finding the distribution of population of phones that violate this specification and as a result, the reduction of the value of a used product and its impact on reliability of components.

- Humidity:

  A high humidity environment can also reduce the reliability of cell phone components and reduce the life. This rating is relatively less significant to a cell phone's value at the EOL, but should be considered. Many phones have a Liquid Contact Indicator that indicate by a change in color of a strip, if a phone has been in contact with water or other liquids. This can severely reduce the value of the phone at the EOL and can often disqualify a phone from being considered for refurbishing.

Gathering data from sensors shortens a cell phones battery life due to an increase in energy overhead, but energy efficient systems can be designed for continuous sensing systems. A data filtering process is also required to reduce storage space and cost of data warehousing. Future research needs to be done to identify the usable data points for each sensor and to convert the data to a common scale for all sensor ratings.

b. Valuation

This example illustrates application of the methodology to a cellphone example using hypothetical product data, shown in Table 1. Future research would gather data and conduct a multivariate regression analysis to determine the exact correlation between sensor data results and residual product value. A single cell phone manufacturer is considered for a cell phone that cost $100 that was sold, with possibly different versions, between 2006 and 2015. A straight line depreciation of 10% per annum is assumed.

Age Rating $w_1 = 0.3$	Battery Usage $w_2 = 0.25$	Accelero-meter $w_1 = 0.25$	Temperat-ure $w_1 = 0.10$	Humidity $w_1 = 0.10$	Current Method Value	Cloud-Based Method Value	Difference in Value
80.00	35.08	57.81	35.59	16.93	$80	$52	$28
0.00	68.64	63.81	52.38	22.79	$0	$41	$41
20.00	64.80	73.31	10.89	18.78	$20	$43	$23
90.00	53.10	29.10	52.08	34.60	$90	$56	$34
30.00	65.28	56.01	54.21	59.77	$30	$51	$21
40.00	29.56	62.68	23.05	41.65	$40	$42	$2
20.00	44.67	28.33	45.47	73.06	$20	$36	$16
60.00	62.73	77.30	56.47	20.24	$60	$61	$1
20.00	29.11	69.68	51.89	48.99	$20	$41	$21
50.00	24.57	73.04	43.67	42.96	$50	$48	$2
						Mean =	$18.72

Table 1: EOL Value

The rating for sensors follows a 0 to 100 scale, with 100 being the best possible score, which means the output of that particular sensor did not sense any faults. A mobile phone which was never dropped during its lifecycle and no free falls were detected has a score of 100. A mobile phone which was dropped excessively and has been physically damaged due to the dropping has a score of 0. The best possible and worst acceptable rating would vary based on the product and the significance of that parameter on the resale value, which is to be determined by the manufacturing company. The variables ‘Battery Usage’ and ‘Free Fall’ are considered to be independent of age. However, in practice these variables will be dependent on the ‘Age’ of the product.

The factors affecting the product take-back cost and refurbished equipment sale differs within product categories. The manufacturing company needs to analyze the market, refurbishing costs and customer usage patterns to assign weights to the output of the sensor rating. A combination of heuristics and historical data can be used to assign these weights in the absence of more extensive data analytics. In the case of a cell phone, the weight for the ‘Age’ variable is assumed to be 30%, the ‘Accelerometer’ and ‘Battery Usage’ have weights of 25% each and the ‘Humidity’ and ‘Temperature’ have weights of 10% each. The high weight for ‘Age’ is due to the assumption that in a short lifecycle products such as cell phones, the market value for older phones reduces sharply. The accelerometer and battery usage data have a 25% weight assuming that these parameters indicate the physical condition of the phone and total hours used respectively, both factors being significant in determining the value of the WEEE. All the simulated sensor ratings are assumed to be normally distributed with a mean of 50 and a standard deviation of 20. Further research needs to be performed to determine the actual distributions of these datasets, and if a parameter such ‘Humidity’ should assume a binomial distribution, i.e. it attains a value of 0 if the device has been in contact with water and a value of 1 otherwise. The table also shows the valuation based on a straight line depreciation of 10% under ‘Current Method Value’ and shows the ‘Difference in value’ between the new methods.

After each of the four elements are scaled from 0 to 100 represented as x_i, and a weighted average shown in equation 1 is used to estimate EOL value.

$$\mathbf{EOL_{value} = \sum w_i\, x_i}$$

c. Decision

After calculating the residual value for each phone, the items are arranged in ascending order of the value. Table 1 shows 10 items with the highest value. The company, using its internal method of calculating the number of phones that need to be refurbished, can select these items in order of its value. Therefore, 100% of the phones do not need to undergo inspection and only the phones which are in the best quality condition will reach the customer as a refurbished product. The threshold for differentiating between phones that need to be refurbished or recycled can also be drawn based on the cost of logistics, refurbishing, packaging and selling the refurbished product, so as to only refurbish phones that are profitable.

d. Simulation Results

This section presents simulation results of the proposed methodology. In the current system of product take back, information on the phone’s condition is obtained after the return. The product valuation and determination of quality is done primarily on the age of the phone, which is an approximation that has large errors. The ‘Year’ and ‘EOL Value’ indicate a correlation between age of the phone and its value, but the correlation is not equal to one. There are several phones that are relatively new but have a lesser value than older phones. This is illustrated in Figure 5, where there are newer phones which are to be recycled, represented in blue, are below the threshold, and vice-versa. The figure shows that on average, using age to estimate the value is a heuristic that closely approximates the value as estimated by sensors. The losses are incurred due to the high variance in value each year as shown in the figure.

A simulation of a sample size of 1000 was performed. Table 1 shows a sample of 10 randomly sampled products for the purpose of demonstration. The results showed that on average, $18.47 was the difference in the estimate of value using the current and proposed methods. This, along with Figure 5 show that certain users are underpaid for high value retuned devices, while others are overpaid for low value and poor quality devices. The loss is shared by the customer, in the form of underpayment at the time of return, and the company in the form of sorting, inspecting and additional refurbishing costs. These losses make the system inefficient overall.

Using the proposed method, only the products that are most fit for a second life are considered, therefore reducing transportation, inspection and component replacement costs, and also ensuring that customers are satisfied with refurbished products. This model is not only profitable for manufacturers, but also improves the environmental-conscious image of the brand. By providing refurbished cell phones at a lesser price point, companies can expand their market base that would lead to more profits in the future with an increase in the purchasing power of customers. By manufacturing once and selling twice, companies reduce their impact on the environment and will be better prepared for stricter regulations in the future.

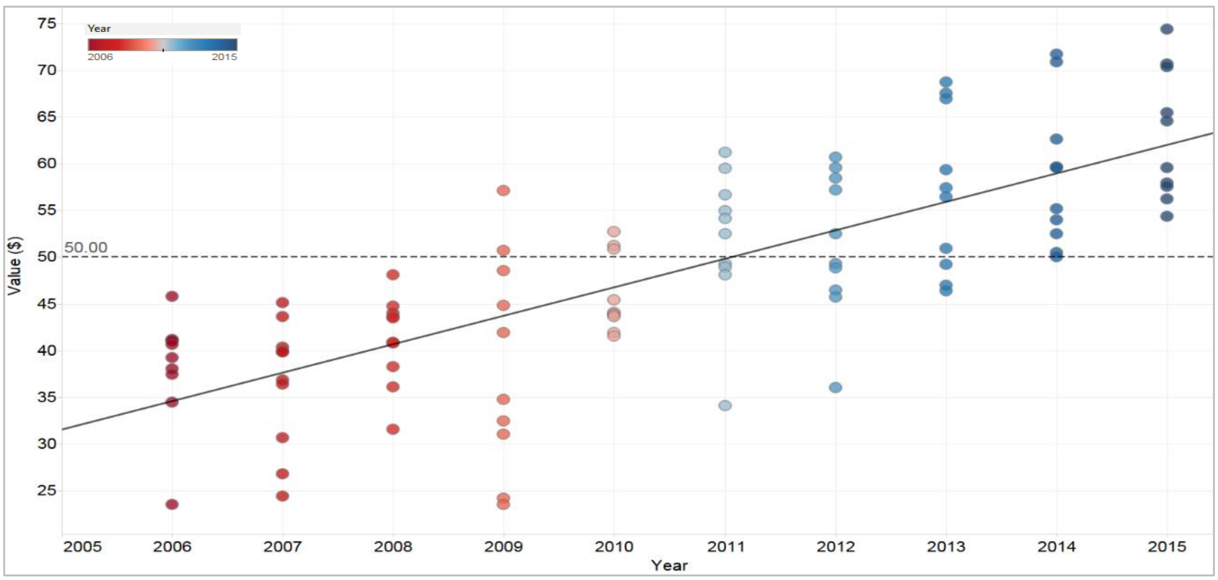

Figure 5: High variance in value of cell phones with similar age but different usage patterns

5. Future Case Study: Medical Devices

This chapter briefly describes considerations for extension of this work to healthcare equipment. Healthcare is still a luxury for many in developing and underdeveloped countries and expensive medical devices remains a major cost of healthcare.

Medical devices are refurbished and sold in the second hand market by certified dealers. These equipment include Ultrasound machines, MRI, CT Scanner, Nuclear Imaging Systems, Heart-Lung Machines, Surgical equipment, CO2 Monitor, Patient Monitor, Pulse Oximeter, AED Defibrillator, Cath Labs, Stretchers and endoscopy equipment.

The refurbished medical equipment market is expected to reach $9.37 billion by 2019 [38]. This growth from 2014 to 2019 is at a CAGR of 12.5%. Refurbishing medical equipment not only reduce waste and environmental impact due to manufacturing, like in the case of cell phone refurbishing, but it also provides low cost equipment to hospitals and medical facilities which would not be able to purchase expensive new equipment. This industry has the potential to grow and add value to society in developing nations, where universal quality healthcare is still highly limited. Emerging markets such as India, Brazil and Mexico will have the highest demand for refurbished medical devices due to their large population, privatization of healthcare and even increasing medical tourism to these countries. G.E. Healthcare and Siemens are the leaders in the refurbished medical devices industry.

Trade-in service or procurement of used equipment, from G.E. Healthcare's website asks for the following questions about the product: Model Name, Serial Number, Year of Manufacture, if the system is in use and if the system is under a service contract. Value estimation is done solely on these data points by the refurbishing company. The company receives products with a high degree of variability in the product type, brand, model number and condition. Since medical devices such as MRI machines are significantly more complex than cell phones, the inspection costs of each component increases. Refurbishing companies use service history and incoming product inspection to identify components and subsystems that need replacement or repair.

Data from sensors can be used to estimate the value of the product and whether it is profitable to procure a used product. It can help the company make a decision tool to decide which product to procure based on the costs associated with refurbishing.

It is important to shift the perspective of procurement managers and policy makers from refurbished devices being old, outdated and of poor quality, to being low cost, reliable and an opportunity to improve healthcare services to the masses.

Part of this ongoing work is going to be published at ASEM 2016 Conference under the paper titled *'Improving Residual Value Estimation for Recovery of Electronic Medical Equipment through Sensor Data Analysis'* by authors Xinlu, Devnani and Thurston.

6. Implications on the Supply Chain and Reverse Logistics

A supply chain of cell phone manufacturing needs to be extended to include a closed loop method which incorporates for the following:

1. Used product returns and acquisitions
2. Reverse logistics
3. Quality inspection and sorting
4. Refurbishing or recycling
5. Resale

The ‘Literature Review’ section touched upon a vast research area within closed loop supply chain for remanufacturing, including demand planning, inventory management, reverse logistics and incorporating the uncertainty in quantity and timing. This thesis does not add to this body of research, instead work is being done to formulate an optimization model of the proposed supply chain with added information on the quantity of the phone, which reduces uncertainty in the end outcome of each product.

Following is a closed loop supply chain model suggested to show the current state of the system and its inefficiencies and later the new proposed model will be introduced to show the net benefit.

Notations:

q_i^n *:* Quantity of new products manufactured and sold

q_i^r *:*Quantity of used products remanufactured and sold

τ *:* Collection rate of used products (new or remanufactured)

α *:* Re-manufacturability rate of single used products

γ *:* Rate of scrapping due to imperfect sorting

p^n *:* Price of new cell phone

p^r *:* Price of refurbished cell phone

p^c *:* Price of cell phone reimbursed to customers

Advancing on the work of Karakayali et. al paper titled 'On the Incorporation of Remanufacturing in Recovery Targets' [39], a closed loop supply chain is proposed in which a company manufactures q_i^n products which are then sold in the market. The company also supplies q_i^r refurbished products in the market. At the end of life, 100% collection rate is unlikely, so collection rate of τ is defined, for both new and refurbished products i.e., products with one and two completed lifecycles respectively. The 'Collector' is defined as the point of return and sorting. At the Collector, products which do have the potential of being reused are sent back to the OEM for refurbishing, represented as $q_i^r \leq \alpha\ \tau\ q_i^n$. As a result, the remaining $\tau(q_i^n + q_i^r) - \alpha\ \tau\ q_i^n$ is sent directly to the recycler to recycle the components into basic materials. The OEM then sends γ of q_i^r to the recycler as the sorting by the Collector is imperfect. The recycler can further sort the products into recycling and disposing, but that is not dealt with in this thesis. It is important to note here that the OEM is responsible for refurbishing and resale. The current system is shown in Fig. 6.

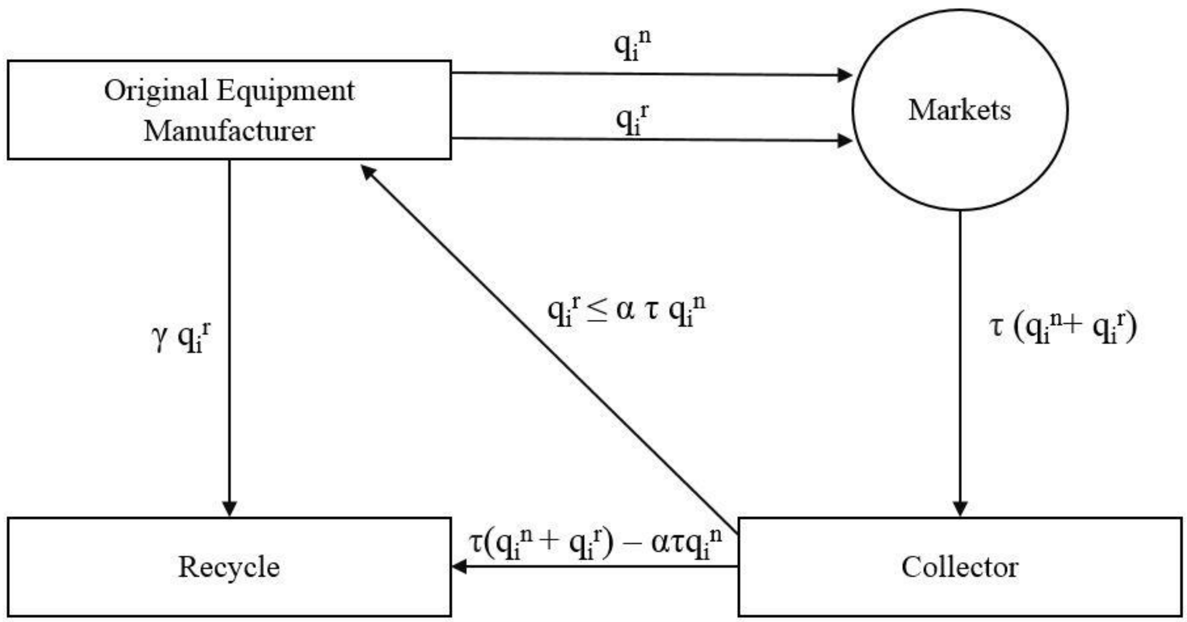

Figure 6: Current Supply Chain of Cell Phone Refurbishing

Now under the new system we assume that the information obtained by sensors is perfect and completely accurate in predicting the end destination of the cell phone. As a result γ' will be 0 as all the cell phones that need to be scrapped, will be done at the point of return or 'Collector' itself. The new optimum values of quantities and overall profit can be determined in this model.

Research is being conducted in collaboration with Dr. Ujjal Mukherjee from College of Business at University of Illinois to formulate this optimization model.

7. Effects on New Product Cannibalization

A major concern with refurbishing of products is that it might lead to a drop in new product sales. This leads to self-competition as the refurbished products often has the same quality and warranty as a new product itself. However, refurbished product sales can enhance the overall profit of the company even though new product sales might drop by a certain amount. By manufacturing once and selling twice, a firm may save on material and overall production costs, thus increasing its profits. Furthermore, if a firm decides against selling or controlling the sales of refurbished products, third party companies might come in to fill in the market demand of the same. Since the quality, pricing and service levels cannot be controlled by the company, the consumer's perception of the brand might alter negatively. The prosed method in this thesis aims to reduce refurbishing costs, thus increasing overall profitability. However, one side effect of having high quality refurbished products, which are almost as good as new, is that it might lead to further cannibalize new product sales.

Remanufacturing or refurbishing is profitable only if the cost of manufacturing is greater than the cost of refurbishing. This paper aims to reduce the cost of refurbishing by providing the company with more information and making the selection of used products more efficient, thereby increasing the overall profitability. By controlling the sale of refurbished phones, the manufacturer prevents other third party firms to make a profit, while controlling the quality and brand image. Refurbished phones, which are sold at a lesser price point, helps capture the lower segments of the market as well. However, the manufacturing company must control the volume and price of the refurbished product to have a global optimum in profit, while reducing the environmental footprint and satisfying the customer's needs.

Many companies use returned products and their components and refurbish the parts to use them in new products. Xerox and Kodak are two such companies which use components from recovered products and reintroduce them in the supply chain. This strategy helps compliment the normal business operations and reduce material, production and processing costs, instead of cannibalizing new product sales. Bosch Tools also uses refurbished products in the market, thereby capturing the lower end of the market and preventing third parties from selling refurbished Bosch products. It might be noted that the risk of new product cannibalization is least when the product is a commercial product, where functionality is the primary factor for purchasing one product over another. Many customers have a strong preference for new products, especially products such as cell phones which are a closely knit part of an individual's lifestyle. This minimizes the impact of cannibalization on new cell phones, and helps capture lower price segments of the market.

Recently, Apple Inc. requested the Indian Government to set up refurbishing facilities in India [40], a market where a lesser price point and high quality cell phone, abet a refurbished one, has potential to grow significantly in the market. India is the second largest smartphone market with 140 million units sold and it is estimated that by 2017, $3 billion out of the $14 billion in sales of refurbished cell phones will happen in India [41] [42].

8. Challenges

A few challenges are listed below:

1. Customer's consent to gathering data:

   One of the major challenge in implementing this system is to get consent from the user or customer to gathering sensor data at all times. Recent controversies in the United States involving the National Security Agency, or the N.S.A. with regards to tracking all phone calls and messages in the U.S. has led to skepticism amongst citizens about an individual's privacy. More recently in 2016, Apple and F.B.I faced a battle in court regarding a case of accessing the data from the cell phone of a terrorist. Apple, with support from many other technology companies, fought to protect all user's data, refusing to provide a master-key to the F.B.I., as it feared that this would be misused to access any individual's phone. This makes it even harder for cell phone manufacturers to request the consent from users in this case. However, data from a phone's G.P.S. sensor which is used for locating a phone is routinely used for the purpose of targeted location based advertisement. For the purpose of the new model proposed in this paper, it is considered less intrusive to a privacy of an individual as personal information and personal communication are completely excluded from the model. The author recognizes the importance of protecting the privacy of users and strongly supports legislation protecting personal information. However, in this model the data collected simply reflects the quality condition of the phone and aim to reduce costs of inspection and logistics in the already existing refurbishing business line. It remains crucial that manufacturers seek the consent and inform the customers about the details of this program, even providing an ‘opt-in or opt-out’ option using incentives. The risk of a leak of sensor data or repurposing this micro-level data for use in targeted advertisement is severe, and it remains the responsibility of the manufacturer to communicate its intentions with the customer base, while showing the benefits to the environment and providing low-cost refurbished cell phones to the market.

2. Data processing and warehousing costs:

   Gathering large sets of data on a daily basis from millions of users will require data management techniques. Raw data, such as that of an accelerometer which indicates the acceleration of the device in all 3 axes, can be processed either at the user’s end or on the cloud, to reduce the number of data points to more a more actionable level. The raw sensor data can be reduced to a single point which indicates a free fall. Similarly, data from the temperature and humidity sensors can be reduced to failures which occur if the level crosses a threshold. This would reduce the total data needed to be stored. The costs of analyzing and defining an accurate model for each product and the cost of data management must be considered.

3. Increased battery consumption:

   The proposed method requires the sensors to be constantly active and record the data which would lead to a reduced charging cycles. A low charge cycle might reduce the customer’s satisfaction and therefore it is important to develop algorithms that can track any changes in the cell phone’s condition, while minimizing its energy consumption.

9. Future Research

A few areas of recommended future research are listed below:

1. Experimentation and model generation for a single and group of products:

   This thesis simply presents a radical new method for cell phone refurbishing, which can be extended to other products where data on product usage is available. However, in order to fully understand which sensors actually impact the value, expected second life quality and reliability, further research needs to be done to validate the 6 sensors used in the model, and the weights assigned to each variable. This can be expanded to include a predictive model which would tell a customer and manufacturer the value of the cell phone while it is being used and predict the value on a future date when the phone would be returned. This is beneficial not only to the company, but also informs the customer about their usage patterns, which remains a strategic decision that the company needs to take.

2. Sensors specifically designed to predict value and quality:

   The current example uses sensors that are present in cell phones for the purpose of being used in applications and enhancing the products functionality. The data from these sensors are being repurposed to predict the value of the product at the EOL. A future research area could be to design a specific sensor that can predict the value with greater accuracy.

3. Cell phone refurbishing – Notifying customers about the condition of their phones:

   The manufacturing company can use the same data it uses to estimate EOL value, and inform the customer the optimal time of returning a phone. Trade-in programs can be customized to satisfy the customers while ensuring that the quality of returned phones are high, thereby increasing remanufacturing profits.

4. Learnings from aviation and aerospace industry:

   Aircraft and engine manufacturers have incorporated sensors for the purpose of safety and maintenance. GE is using the same system for maintenance interventions in turbines and medical devices manufactured by them. According to G.E.'s estimate for each flight, one terabyte of data is produced per flight. The steps of processing, filtering, storing and converting data into actionable data points can be directly learned from such a system and applied to the cell phone case.

5. Automotive Industry:

   New car sales volume in the U.S. were 17.5 million and used car sales volume were 38.2 million in 2015 [43]. Used car sales are more than twice in volume than new cars. However, the automotive resale industry is still inefficient and fragmented. Every car today has around 60-100 sensors which are continuously gathering data. Vehicles also come equipped with On-Board Diagnosis (OBD) adapters which can access data from these sensors and store it on a cloud database. A similar system that is used in cell phones can be implemented by manufacturers or third party companies. Since number of sensors in vehicles are only increasing over time and companies like Tesla aim to have vehicles always connected to the internet, resale valuation of cars can be more efficient using more information than the current system of basing a car's resale value only on the year of build and miles driven.

6. Medical Devices Industry:

   The medical devices industry has already been discussed in a previous section. Further research in this area is recommended because of the potential of the industry to grow, the environmental and social good that the research can bring about.

7. Internet of Things (IoT) and application to different products:

   IoT has expanded the use of sensors into various consumer goods. Now refrigerators and washing machines come equipped with sensors and are always connected to the internet. The same principles mentioned before for cell phones, medical devices and cars can be applied to various other consumer and commercial goods. Sensors are already being used to notify service providers about maintenance requirements and part failures, but the same data can be extended to be used in determining the value at the EOL.

8. Pricing:

   The pricing system currently being followed is based on an averaging method of all cell phones that are returned since phones vary in their value. But future research can be performed on finding out optimal pricing methods based on the new information. Another option which a company may implement is to provide variable pricing which is dependent on the condition of the phone when it is returned, in order to reward customers who return the devices in a superior condition. It will also be useful to include market demand for both new and refurbished products in this research to obtain a holistic model.

9. Misuse of data by manufacturers:

   Selling data to third party companies, for example if a user continuously drops the phone, that individual can be targeted more by insurance companies. Companies like Google already target users based on their location, which is accessed by Google servers. This enables locally targeted advertisement, such as restaurants in a region. The consent of the user to share this level of sensor data must be explicit.

10. Combining with other data sources:

    There is an opportunity to link this sensor data with other service and maintenance data. This is especially useful in the medical devices industry where routine servicing is contracted to the OEM or other service providers. This data about replacement of components and routine wear and tear can be recorded and combined with the sensor data through the lifecycle.

11. Profitability of this model:

    Another area of future research could be to validate this model by performing a Cost-Analysis to prove that the benefits of implementing such a system is better than the previous method of procurement and quality inspection. Additional costs such as data modeling and warehousing needs to be included to show the profitability.

12. Reframing the objective from point of view of environmental good:

    This thesis attempts to solve a business problem and plug inefficiencies in the refurbishing business. However, a future research topic would be to evaluate the reduction in environmental footprint as the objective.

10. Conclusion

This paper presented a method for using data gathered by sensors during customer-use of a product in order to develop a more accurate estimation of the product's value than is currently obtained using age-related heuristic rules of thumb. The limitation of this paper is that the distributions of the sensor data is not known, and is only assumed. The absence of real-world data has led the authors to assume weights of each sensor data's contribution to the final value. Future work includes incorporating EOL information into the full reverse logistics and remanufacturing system, and engaging the consumer in the decision as to when to trade in older products for new ones.

For CEOs of cell phone manufacturing companies, this model can help reduce costs, reduce the environmental impact, comply with government regulations, increase sales in lower price segments of the market and thereby increase profits. It remains critical to have the customer's consent for gathering data and protecting this data. This can also be an opportunity for third party refurbishing companies to use this data and create a hub for manufacturers to outsource the used cell phone business.

As we move to an even more connected world with the growth of the Internet of Things and the number of connected products in an individual's life keeps increasing, this system can enable the electronics, medical devices and automobile industries towards reducing its consumption of resources, better utilize existing products, reduce refurbishing costs, exceed the government's recycling requirements, grow net profits and move towards a more sustainable future.

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