Disassembling and Remanufacturing End-of-Life Sensor Embedded Cell Phones

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Abstract: This paper investigates and compares the benefits of sensor embedded cell phones (SECPs) over conventional cell phones (CCPs) in product recovery. Sensors embedded into cell phones during the production process are important data acquisition tools for condition monitoring during the product life cycle. SECPs provide reduction in the costs of disassembly, inspection, inventory, and stock-outs. With the data captured from sensors, the recovery system is able to detect failed or missing components in SECP before disassembling it. In addition, the captured data can be used to estimate the remaining lives of components and cell phones. In order to ascertain the impact of sensors on the performance of processes involving disassembly and remanufacturing, two separate and detailed discrete event simulation case studies with experiments based on orthogonal arrays (OAs) are carried out for the CCPs and the SECPs. The results are then compared for the two cases. Results confirm that sensors are greatly beneficial in reducing the processing costs. The paper concludes by determining the extent of the benefit of using sensors which provide an upper limit of the cost of the sensors for the SECPs to remain viable.

Key Words: Product recovery, closed-loop supply chain, remanufacturing, sensor embedded products, disassembly

1. Introduction

Environmental concerns have been a topic of interest of researchers in recent years. These concerns have found their way into the manufacturing arena as well. While technology has advanced and has brought comfort for humans, it often results negatively on the environment at the end of their lives because the products at that stage are typically discarded. However, in many cases, that option quickly became infeasible because of the decreasing number of available landfills. Besides, this was neither a safe nor a sustainable option because the products which were being landfilled contained hazardous materials and components making the process harmful for the environment. As a result, there has been a push towards product recovery. Product Recovery aims to minimize the amount of waste sent to landfills by recovering materials and parts from old or outdated products by means of recycling and remanufacturing.

The first operation in the recovery of products is disassembly which comprises the separation of the desired components, subassemblies, and materials from end-of-life (EOL) products. Disassembly operations can be performed at a single workstation, in a disassembly cell, or

on a disassembly line.

Although a single workstation and disassembly cell is more flexible, the highest productivity rate is provided by a disassembly line. In addition, a disassembly line is more suitable for automated disassembly. The number of components that can be recovered from a product on a disassembly line is highly uncertain due to missing and/or non-functional components. Since there is generally no information available on the condition of components prior to disassembly, components need to be inspected following disassembly. Depending on the inspection times, inspection costs can be a significant burden on the profitability of a disassembly line. Moreover, if the component is determined to be non-functional at the end of the inspection process, the time and resources spent to disassemble the component are wasted. This increases the disassembly cost as well as the backorder cost. By increasing the safety stock levels of components as a remedy for high backorder costs results in higher holding costs.

Recent literature has offered a solution to this problem where sensors may be embedded into products while producing (assembling) them. The sensors can then capture and record lifetime usage data of the product. The captured data can be instrumental in estimating the remaining lives of the components or the product. In addition, it may also provide information about the missing and/or broken components.

This paper investigates and compares the benefits of sensor embedded cell phones (SECPs) over conventional cell phones (CCPs) in product recovery. SECPs provide re-

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(Received August 20, 2015)
(Revised October 20, 2015)
(Accepted November 5, 2015)

duction in the costs of disassembly, inspection, inventory, and stock-outs. With the data captured from sensors, the recovery system is able to detect failed or missing components in SECP before disassembling it. In addition, the captured data is used to estimate the remaining lives of components and cell phones. In order to ascertain the impact of sensors on the performance of processes involving disassembly and remanufacturing, two separate and detailed discrete event simulation case studies with experiments based on orthogonal arrays (OAs) are carried out for the CCPs and the SECPs. The results are then compared for the two cases.

The next section provides a brief literature review. Section 3 describes the CCP and the SECP systems in detail. Section 4 gives the details of the simulation experiments. Section 5 discusses the numerical results. The last section presents some concluding remarks.

2. Literature Review

This section includes the review of environmentally conscious manufacturing and product recovery (ECMPRO), disassembly, remanufacturing, use of RFID technology in supply chains and closed loop supply chains, and sensor embedded products. Two important review papers are available in the literature and are related to the subject area of this paper. The first one by Gungor and Gupta (1999) is the state of the art survey paper covering papers in Environmentally Conscious Manufacturing and Product Recovery (ECMPRO) published through 1998. The second one by Ilgin and Gupta (2010a) is also the state of the art survey paper in the same area covering papers published between 1998 and 2010. Together, they classified more than 870 papers (330 and 540 respectively) under four main categories, viz. environmentally conscious product design, reverse and closed-loop supply chains, remanufacturing and disassembly.

Disassembly is a key process in this study and hence an overview of the disassembly literature is provided here. Gupta and McLean (1996) provide an overview of the research in the area of disassembly of products. Disassembly operations can be performed on a disassembly line or in a disassembly cell. Gungor and Gupta (2002) studied this issue and concluded that disassembly lines are the best choice for large scale product recovery of EOL products. Torres et al. (2004) considered the automation of a PC disassembly in a cell. Optimum disassembly sequencing is crucial in making the disassembly operation profitable. A survey on disassembly sequencing was presented by Lambert (2003).

Srinivasan et al. (1999) and Mascle and Balasiou (2003) used a wave propagation technique to obtain optimal solutions for selective disassembly. Chung and Peng (2005) investigated the efficacy of the wave propagation approach for selective disassembly. Kara et al. (2006) improved the selective disassembly approach and introduced visible disassembly sequencing. Kim et al. (2006) used adaptive disassembly sequencing for home appliances. McGovern and Gupta (2006) applied ant colony optimization method to solve the disassembly sequencing problem. Andres et al. (2007) proposed a two-step optimization method in

order to find the optimum disassembly sequence for a disassembly cell. Altekin et al. (2008) used a mathematical programming model to achieve maximum profit while balancing a disassembly line. Barba-Gutierrez et al. (2008) included lot sizing in reverse material requirements planning for scheduling disassembly. Tripathi et al. (2009) applied Self-Guided Ants algorithm for disassembly sequencing. Ding et al. (2010) improved the ant colony algorithm application in disassembly sequencing by adding Pareto approach.

There have been a few papers pertaining to cell phone disassembly and remanufacturing. For example, Gupta et al. (2004) proposed an algorithm to select the optimal sequence for disassembling a cell phone. Seliger et al. (2004) used both simulation and integer linear programming for remanufacturing a cell phone and collected statistical data from a mobile replacement case in Western Europe.

RFID tags and sensors can provide unique information about the structure of the products as well as the information collected on the working conditions during the working phase of the products. RFID tags and sensors have been widely used in many industries and service applications. They can also be very useful in supply chain management. Angeles (2005) considered these applications and presented several case studies. Ngai et al. (2008) reviewed the literature on RFID applications in production supply chains. Ngai (2010) provided specific information on the use of RFID in production and supply chains. Jun et al. (2007) introduced closed-loop product life cycle management to provide information on the products during their life cycles. Visich et al. (2007) demonstrated the significance of using RFID in product recovery in closed-loop supply chains. Behret and Korugan (2009) presented a simulation study to show the quality impact of returned products in a hybrid remanufacturing system.

Sensors have more practical use in closed-loop supply chains because they can sense and store information about the conditions of the components during the life cycles of the products. Vadde et al. (2008) represents one of the earliest examples of sensor applications in product recovery. They used sensors to gather information on the status of the products during their useful lives. They demonstrated that sensors are beneficial when products are returned and recovered because they provide valuable information prior to disassembly and remanufacturing. Kongar and Gupta (2006) suggested that disassembling according to a specific demand would be more efficient under uncertain conditions.

Ilgin and Gupta (2010b) evaluated the use of sensors during EOL processing of products. To be more specific, they studied the impact of sensor implementation on different performance criteria for a multi-product appliance disassembly line controlled by a multi-kanban system. They conducted experiments based on orthogonal arrays (OAs) for sensor embedded products and conventional products. Discrete event simulation was used to model the experiments for both types of products, namely, without and with sensors embedded in them. The results illustrated that disassembly, inspection, disposal, backorder, transportation and holding costs for sensor embed-

ded products were less than conventional (without sensor embedded) products. Ilgin and Gupta (2011a,b,c) adapted similar approach to various products including dish washers, air conditioners, dryers and computers. Different Kanban approaches were used depending on whether the case involved single product or multiple products. Ilgin and Gupta's studies were only limited to the disassembly portion of processing large EOL products.

Ondemir et al. (2012) proposed an optimization model in which EOL products were disassembled and classified into different quality bins based on the conditions of the EOL products and their remaining lives. The goal of their model was to minimize the cost to meet the demand of remanufactured products having different quality levels. Selecting the proper components from collected EOL products and assembling them was the main idea of this study. Ondemir and Gupta (2013a) applied fuzzy programming to one of their past studies in order to accommodate uncertainties. Ondemir and Gupta (2013b) found a solution to the remanufacture-to-order problem by using mathematical programming. Ondemir and Gupta (2012) implemented Genetic Algorithm to solve a similar optimization model involving remanufacturing. Ondemir and Gupta (2014a) applied Linear Physical Programming for the remanufacturing of the products. Ondemir and Gupta (2014b) adopted the Internet of Things approach and solved the remanufacturing problem to recover EOL products. Ondemir and Gupta's studies were limited to the remanufacturing portion of processing large EOL products in a static environment.

The study reported in this paper includes both disassembly and remanufacturing portions of processing EOL cell phones (which is a small EOL product) in a reverse supply chain environment with continuous flow (which is a dynamic environment).

3. Methodology

This section describes the CCP and SECP systems studied here. The details of their disassembly and the remanufacturing processes are also highlighted.

3.1 Disassembly and Classification

The EOL cell phones are collected from customers and brought to the disassembly facility. There they are disassembled using a five station disassembly line. This is because cell phones are assumed to have five major components namely, back cover, battery, circuit board, audio set, and screen, each disassembled at a separate station in a particular sequence shown in Figure 1. This process is similar for both (CCP and SECP) systems. The main difference in SECP system is that components which are not reusable are not disassembled. After a component is disassembled, it is inspected to determine its condition. In the CCP system, it is inspected manually while inspection is not needed in SECP system since sensors provide the condition information of the components. Inspection basically confirms the reusability of the component. If the component is not reusable, it is either recycled or disposed of. If the component is in good condition the quality level of this component is determined manually in CCP. Quality

level in SECP is determined based on the data captured by the embedded sensors. The data can be interpreted using software where the remaining life of the components can be estimated. Remaining life can be interpreted as quality level (Ondemir and Gupta, 2013b). The component is then categorized into one of three classes termed as high, medium or low quality and is placed into one of three bins known as high, medium or low quality level bins. A component which has a remaining life of at least 3 years is accepted as high quality component. Medium quality component has a remaining life from 1 to 3 years and low quality component has a remaining life of 6 months to 1 year. Since sensors capture this data from the components, inspection time and cost can be saved in the SECP system.

3.2 Remanufacturing

Disassembled and inspected components are sent to the remanufacturing area. They are reassembled based on their quality levels. The remanufactured cell phones are used to fulfill the demand. In addition, the components which are in good condition are used to fulfill the components demand. Figure 2 shows the flow of the disassembled components.

4. Simulation Experiments

In order to compare the CCP and SECP systems 63 factors were taken into account. Each of the factors had two levels. They are divided into six categories and presented in Tables 1 through 6.

Since price is an important factor to calculate the profit, it was included in the factors. The levels of prices for high quality (HQ) and medium quality (MQ) remanufactured cell phones and disassembled components can be seen in Table 1. Low quality levels were not included because their demand tends to be low and thus could be ignored.

Demand is dynamic in the system and is assumed to be uniformly distributed. It also affects the profit of the two systems. Average demand levels can be seen in Table 2.

Table 1 Price Factors and Levels

Factor	Level 1	Level 2
Price of HQ Audio Set (\$)	3	5
Price of HQ Back Cover (\$)	7.5	10
Price of HQ Battery (\$)	17.5	25
Price of HQ Circuit Board (\$)	80	100
Price of HQ Cell Phone (\$)	350	400
Price of HQ Screen (\$)	75	100
Price of MQ Audio Set (\$)	1	2
Price of MQ Back Cover (\$)	4	5
Price of MQ Battery (\$)	10	13
Price of MQ Circuit Board (\$)	45	60
Price of MQ Cell Phone (\$)	175	250
Price of MQ Screen (\$)	60	70

Cost factors with their levels are shown in Table 3.

The conditions of the components are integrated into the system based on probability distribution. They are considered as factors because they have direct impact on the flow and remanufacturing of cell phones. These factors and their levels can be seen in Table 4. Low quality level

Fig. 1 Flow of EOL Cell Phones and Disassembled Components

Fig. 2 Decisions Before Remanufacturing

Table 2 Demand Factors and Levels

Factor	Level 1	Level 2
HQ Remanufactured Cell Phone Demand Rate	3	6
MQ Remanufactured Cell Phone Demand Rate	2	4
HQ Back Cover Demand Rate	3	6
MQ Back Cover Demand Rate	5	10
HQ Battery Demand Rate	5	10
MQ Battery Demand Rate	3	6
HQ Screen Demand Rate	7	14
MQ Screen Demand Rate	4	8
HQ Audio Set Demand Rate	3	6
MQ Audio Set Demand Rate	2	4
HQ Circuit Board Demand Rate	6	12
MQ Circuit Board Demand Rate	4	8

probabilities are not shown in Table 4 because once the probabilities are set for high and medium quality levels, the probability of the low quality can be found by subtracting the sum of those two from 1.

Table 5 shows the disassembly, inspection and response times for each component of a cell phone. Response time is the time required to receive the information from sensors. It is used only in SECP while inspection time is used as

Table 3 Cost Factors and Levels

Factor	Level 1	Level 2
Disassembly Cost (\$ /min)	1	2
Assembly Cost (\$ /min)	1.2	1.5
Disposal Cost (\$ /lbs)	0.3	0.5
Inspection Cost (\$ /min)	0.4	0.6
Holding Cost Rate	0.1	0.3
Backorder Cost Rate	0.4	0.8

factor only in CCP.

Recycling is one of the ways to generate revenue in the system. Scrap revenue per unit is shown in Table 6. The components are recycled if they are not reusable. However, not all components can be recycled because some of the components contain hazardous materials. Thus, recycling rate is used for circuit board and is considered as one of the factors. Assembly time for remanufacturing is considered as a factor as well. They are all shown in Table 6.

A comprehensive study was needed to quantify the improvement achieved by the SECPs over CCP. Since there are 63 factors, each at two levels, a full factorial design would require a prohibitive number of experiments to be carried out. Therefore, the number of experiments was reduced to 64 using orthogonal arrays. Specifically, L64(263)

Table 4 Probability Levels

Factor	Level 1	Level 2
Probability of Collecting Reusable Audio Set	0.4	0.6
Probability of Collecting Reusable Back Cover	0.2	0.3
Probability of Collecting Reusable Battery	0.3	0.45
Probability of Collecting Reusable Circuit Board	0.4	0.6
Probability of Collecting Reusable Screen	0.3	0.45
Probability of Collecting HQ Audio Set	0.2	0.3
Probability of Collecting MQ Audio Set	0.4	0.6
Probability of Collecting HQ Back Part	0.1	0.15
Probability of Collecting MQ Back Part	0.4	0.6
Probability of Collecting HQ Battery	0.1	0.15
Probability of Collecting MQ Battery	0.3	0.45
Probability of Collecting HQ Circuit Board	0.2	0.3
Probability of Collecting MQ Circuit Board	0.4	0.6
Probability of Collecting HQ Screen	0.2	0.3
Probability of Collecting MQ Screen	0.4	0.6

Table 5 Disassembly and Inspection Times

Factor	Level 1	Level 2
Disassembly Time of Audio Set (seconds)	7.5	10
Disassembly Time of Back Cover (seconds)	4	6
Disassembly Time of Battery (seconds)	1	2
Disassembly Time of Circuit Board (seconds)	30	45
Disassembly Time of Screen (seconds)	45	60
Inspection Time of Audio Set (seconds)	3	5
Inspection Time of Back Cover (seconds)	7	10
Inspection Time of Battery (seconds)	20	30
Inspection Time of Circuit Board (seconds)	30	45
Inspection Time of Screen (seconds)	15	20
Response time of sensor, Audio Set (seconds)	2	3
Response time of sensor, Back Cover (seconds)	2	3
Response time of sensor, Battery (seconds)	4	5
Response time of sensor, Circuit Board (seconds)	10	12
Response time of sensor, Screen (seconds)	10	13

orthogonal array was chosen since it requires 64 experiments while accommodating 63 factors with two levels each (Phadke, 1989). The two systems were modeled using discrete event simulation. Arena 14.5 was used to run these models (Kelton and Sadowski, 2007). The models were run for 4008 hours by using 5 replications to reduce

Table 6 Scrap and Assembly Factors

Factor	Level 1	Level 2
Scrap Revenue (\$ /lbs)	0.2	0.4
Rate of Recycling for Circuit Board	0.3	0.4
Assembly Time for Cell Phone (minutes)	2.5	3

the impact of variations in the systems.

5. Numerical Results

This study was designed to estimate the economic value of the sensors embedded in cell phones. In order to find the value of the sensors, the profit difference between two systems were recorded with each experiment and averages and ranges were revealed to see the significance of this value. Total profit is calculated as follows:

$$TotalProfit = TotalRevenue - TotalCost \quad (1)$$

Total revenue consists of 3 terms including remanufactured cell phone sales revenue (RCPSR), component sales revenue (CSR) and scrap revenue (SR). RCPSR is the sum of sales of all quality levels remanufactured cell phones. CSR is the total component sales revenue. SR is the revenue which is generated by recycling the components that are not reusable. Thus, total revenue is as follows:

$$TotalRevenue = RCPSR + CSR + SR \quad (2)$$

Total cost is the sum of all costs incurred during disassembly, inspection, and remanufacturing processes. Disassembly cost (DC) is calculated based on disassembly time needed for EOL cell phones. Its unit cost per time period includes labor, setup and machine costs. Although the systems do not consider transportation and collection processes, collection cost (CC) is included in the total cost function for each EOL cell phone arriving at the facility. Disposal cost (DiC) is incurred while disposing components that are neither reusable nor recyclable. Assembly cost (AC) is the reassembly process cost to remanufacture cell phones from disassembled components. Inspection cost (IC) is the core of this study since sensors are expected to eliminate inspection. Holding cost (HC) is the cost to keep the remanufactured cell phones and disassembled components in inventory when there is no demand. Backordering cost (BC) is the stock-out cost when demand for remanufactured cell phones or dissembled components cannot be fulfilled. Inventory level is limited to a maximum number so that it would not exceed the storage capacity in the system. Thus, the total cost is as follows:

$$TotalCost = DC + CC + DiC + AC + IC + HC + BC \quad (3)$$

Once total profit for each experiment was determined using the averages of replications of simulation runs, the differences of two system performances were calculated. The differences can be seen in Table 7 with ranges and averages. Sensor value was calculated by dividing the difference in total profit by the total number of sensors used in the proposed system. This value can be seen as 2.14 in Table 7 which means that the price of a sensor should

not exceed 2.14 for it to be viable and profitable if implemented in cell phones. Sensor value ranges from -0.02 to 8.66. Most profitable experiment had \$8.66 as sensor value. Total profit difference was \$40,277.76 on average. These showed that there is a significant increase in total profit when the SECP system is used.

Table 7 Comparison of Results

Comparison	Range (\$) [SECP-CCP]	Average (\$)
Sensor Value	[-0.02, 8.66]	2.14
Total Profit	[-498.69, 173276.30]	40277.76
Disassembly Cost	[-54482.80, -14343.60]	-30225.5
Inspection Cost	[-21617.10, -8537.00]	-13887.3
Holding Cost	[-640.87, 466.68]	-17.45
Backordering Cost	[-940.54, 420.51]	10.33

The difference in total profit occurred because of the savings in disassembly and inspection costs. Disassembly cost reduction was \$30,225.50 on average. It ranged between \$14,343.60 and \$54,482.80. Inspection cost was reduced by \$13,887.30 on average. By analyzing the results, it can be seen that inspection can be eliminated by means of sensors. These reductions are the main factors affecting the economic value of sensors. Inventory and stock-out costs changes did not lead to noticeable improvement.

6. Conclusion

This paper evaluated the benefits of sensors when embedded into cell phones. SECPs were compared with CCPs and their economic benefits were highlighted. Sensors were found to be instrumental in reducing disassembly and inspection costs.

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