Impact of the quality and cost of information on the reverse supply chain

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Abstract

We analyze the relation between the value captured from returned products and the amount of information available on product quality. We show that increased information accuracy may lead to a decrease in the proportion of product recycled; and investments in information acquisition technology may result in optimally lower accuracy overall.

1 Introduction

Due to relaxed return policies, environmentally conscious consumers, and international legislation requiring retailers to take back end-of-life products, companies are faced with an ever growing stream of returned products and are looking for novel ways to recapture value from it [13]. Some returned products or parts will be of sufficient quality to warrant some form of recovery, thus accruing value to the firm; other

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parts or products are simply disposed. A key stage in the process is inspection to determine product quality in relation to remanufacturing/refurbishment/recycling. For a broad review of research on reverse logistics, please see [8, 7, 4, 9, 6, 11, 12].

The rapid development of sensing, data-logging and wireless devices is making the gathering of information on the availability, condition and location of products in the returns stream possible and increasingly affordable. This has opened up the possibility of earlier and more accurate identification of recyclable units, thus streamlining the reverse supply chain. While media coverage and many industry reports have suggested that great benefits to supply chain management in general will be unleashed with the use of Information Acquisition Technology (IAT), including RFID, sensing and data-logging devices, these benefits have not been substantiated with accurate, model-based analysis. Özer and Lee [10] point out this credibility gap (in relation to RFID) and summarize a number of areas where modeling efforts have been undertaken. This gap is even more apparent when it comes to the reverse supply chain [1].

The objective of this paper is to explore the impact of information – specifically the quality of information on the state of returned products – on the recycling/disposal decision of a company. We illustrate some of the complexity involved in determining how information impacts the reverse supply chain and how its effect is highly dependent on the structure of value recovery and the cost of collecting information. In particular, we show that (1) increasing the quality of information has ambiguous impacts on the proportion of goods that are recycled; and (2) the adoption of IAT may lead to optimally lower quality information overall.

2 The model

We consider a profit maximizing firm facing a stream of returned product. The firm can decide to "recover" or dispose of each product. We define "recovery" to include direct recovery, such as re-use; refurbishing/remanufacturing; or end-of-life recovery such as parts retrieval or recycling. The quality of a returned product is represented by the random variable Γ, which we normalize to be on the range $[0, 1]$. The value of recovering a good of quality $\Gamma = \gamma$ is $V(\gamma)$, where we assume that V is increasing in γ, and $V(0) < 0 < V(1)$. This value function includes both the cost of recovery and the benefits of successful recovery. Thus, the value of recovering a low quality good is negative – it has costs but no benefit; while the value of recovering a high quality good is positive – the benefits outweigh the costs. We assume that the cost of disposal is independent of the quality of the good – it costs no more to dispose of a working part than of a broken part. Thus for simplicity we normalize the value of disposing to 0.

Unfortunately, identifying the true quality, γ, of the returned product requires costly inspection and testing, and is often error-prone. Consequently, before deciding whether to recover or dispose, the firm will only receive a signal to the true quality with a certain level of accuracy. Let the signal be denoted by Y_θ (also on the range $[0, 1]$ for simplicity), where θ measures the quality of the signal, i.e. the accuracy level of the inspections. The signal is a random variable defined on the same sample space as Γ, and therefore may provide some information about Γ.

The expected value to the company of a product with signal $Y_\theta = y_\theta$ is $\mathrm{E}[V(\Gamma)|y_\theta]$. We assume that the signals can be ordered from bad to good, so that $y_\theta^H > y_\theta^L \Rightarrow \mathrm{E}\left[V(\Gamma)|y_\theta^H\right] > \mathrm{E}\left[V(\Gamma)|y_\theta^L\right]$. The firm will choose to recover if the signal indicates that the expected value of recovery is positive; and dispose otherwise. Let

γ^* represent the lowest quality good that has a positive value of recovery, and y_θ^* the lowest signal that indicates that the expected value of recovery is positive: $y_\theta^* \equiv \min\{y_\theta : \mathrm{E}[V(\Gamma)|y_\theta] \geq 0\}$. Assuming a risk neutral firm, we have that if a returned product has signal $y_\theta \geq y_\theta^*$ it will be recovered, and otherwise it will be disposed of. Let $F^\theta(\cdot,\cdot)$ be the joint cumulative probability distribution over Γ and Y_θ; $F_y^\theta(\cdot)$ is the marginal probability distribution of Y and $F_{\gamma|y}^\theta(\cdot)$ is the conditional probability distribution of Γ given $Y = y$.

Since the firm will dispose and receive zero value for any signal $y < y_\theta^*$, the firm's expected value from a random returned product before receiving any signal is:

$$\begin{aligned}
&\int_{y_\theta^*}^1 \int_{\gamma=0}^1 V(\gamma)\, dF_{\gamma|y}^\theta(\gamma|y_\theta)\, dF_y^\theta(y_\theta) \\
&= \int_{y_\theta^*}^1 \mathrm{E}[V(\Gamma)|y_\theta]\, dF_y^\theta(y_\theta) \\
&= \mathrm{E}[\mathrm{E}[V(\Gamma)|Y_\theta \geq y_\theta^*]] \\
&= \Pr[Y_\theta \geq y_\theta^*]\, \mathrm{E}[V(\Gamma)|Y_\theta \geq y_\theta^*] \qquad (1)
\end{aligned}$$

The proportion of goods that are recycled is equal to $\Pr[Y_\theta \geq y_\theta^*]$.

3 Optimal recovery/disposal decision

Our first question is how the quality or accuracy of the product information is likely to impact the recycle/disposal decision. In mathematical terms we are asking how the accuracy θ of the information is related to $\Pr[Y_\theta \geq y_\theta^*]$. We show here that how the firm's behavior changes with a more informative signal is ambiguous. Consider a firm whose value of recycling a product of quality $\Gamma = \gamma$ is $V(\gamma) = \gamma - 0.6$, and

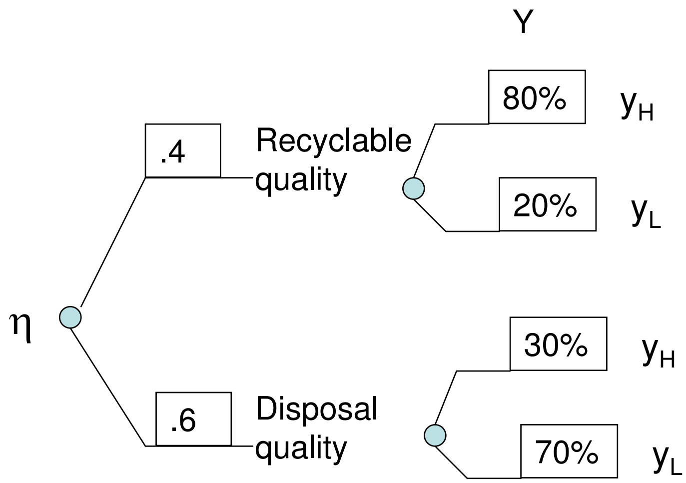

Figure 1: A Semi-Informative Signal Y and the true quality Γ

$\Gamma \sim U[0,1]$. Then $\mathrm{E}[\Gamma] = 0.5$, and $\mathrm{E}[V(\Gamma)] = -0.1$. With no information the firm would dispose of all units. With perfect information the firm would recycle all units in which $\gamma \geq 0.6$ (that is, 40% of the units) for an expected value to the firm of 0.08. The firm increases the proportion of recycled units when they move from no information to perfect information; and we can equally conclude that the firm will weakly increase the proportion of recycled units when they move from no information to some information. (In fact, this is true for all firms that dispose of all units under no information. Conversely, all firms that recycle all units under no information will decrease the proportion recycled under perfect information.) However, we cannot conclude that the firm will recycle more as they gain more information in general. Consider the signal represented in Figure 1. A "high" signal, y^H, implies that it is more likely that the product is recyclable, while a "low" signal, y^L, indicates otherwise. Specifically, if $\gamma \geq 0.6$ then $Y = y^H$ with probability 0.8, and y^L with probability 0.2; if $\gamma < 0.6$ then $Y = y^H$ with probability 0.3, and y^L with probability 0.7.

The probability of getting a signal $Y = y^H$ is 50%, and the $\mathrm{E}\left[V(\Gamma)\,|Y = y^H\right] = 0.02 > 0$, so the firm will recycle 50% of the units with an expected value to the firm of .01. Thus, with no information, the firm recycles nothing, with a semi-informative signal, the firm recycles 50%, with perfect information the firm recycles 40%.

4 Optimal inspection accuracy

In this section we explore how a firm's optimal inspection accuracy level θ depends on prior investment that impacts the cost of collecting information. For instance, investments in information acquisition technologies and design for disassembly and/or inspection will reduce the cost of gathering product information in different ways. It is thus important to assess the effect that these design choices will have on the optimal levels of information and recycling. The firm faces the following problem when choosing the accuracy of inspection:

$$\max_{\theta} \Pr\left[Y_\theta \geq y_\theta^*\right] \mathrm{E}\left[V(\Gamma)\,|Y_\theta \geq y_\theta^*\right] - c(\theta) \tag{2}$$

where increasing θ increases the sensitivity and specificity of the signal, but has an increasing cost, $c(\theta)$. (For this problem an accuracy level θ^H is more informative for all firms, in the Blackwell [2, 3] sense, than an accuracy level θ^L if and only if it is more sensitive and more specific. See Appendix for proof.) Note that in general this problem is not well behaved. It is well known that the value of information is often non-concave [5]. In particular, the value of "small" amounts of information tends to be zero: a very noisy signal does not change the optimal action. For this analysis, we focus on the case where an interior solution for (2) exists and is optimal. That is, we assume that the firm is performing some type of inspection. Under this assumption, the firm will choose an accuracy level where the marginal value of the increased information is equal to the marginal cost of improving the signal. Now, consider the impact of a prior investment in IAT.

We model the presence of IAT as having an impact on the cost of accuracy $c(\cdot)$. We assume that IAT requires a fixed investment up-front, but then reduces the cost of inspection accuracy, $c(\theta)$, by providing some information at zero (or very low) marginal cost. For example, for a fixed cost per printer a firm can install page counters. On each returned printer the firm would get a signal – the number of pages printed – essentially for free. Figure 2 illustrates one way in which IAT may impact the cost of inspection accuracy. The left hand side shows the cost of achieving accuracy θ, before and after IAT (after marked with a ˜). In this illustrative example, IAT pivots the cost curve to the right: it provides imperfect information about quality, but in order to gain perfect information, one must actually open up the good and inspect it. Thus, IAT has no impact on the cost of perfect information. The right hand side shows the associated *marginal* cost of achieving accuracy θ, as well as the optimal level of accuracy for firms with a low- or high-marginal value of information. In this case, a firm with a high marginal value of information would actually demand less information after IAT.

The intuition is that before IAT it may have been optimal to fully disassemble every good; after IAT the firm has a good signal about which goods they will dispose, and therefore dispose directly without disassembly. Note that this is just one possible way that IAT can impact the cost of accuracy – how it actually impacts it depends on both the current inspection technique and the data provided by the IAT.

Compare this with a prior investment in design for disassembly (DfD). DfD will also impact the cost of accuracy, through making it easier to disassemble and inspect parts. Unlike IAT, however, DfD will most likely lower the marginal cost of accuracy

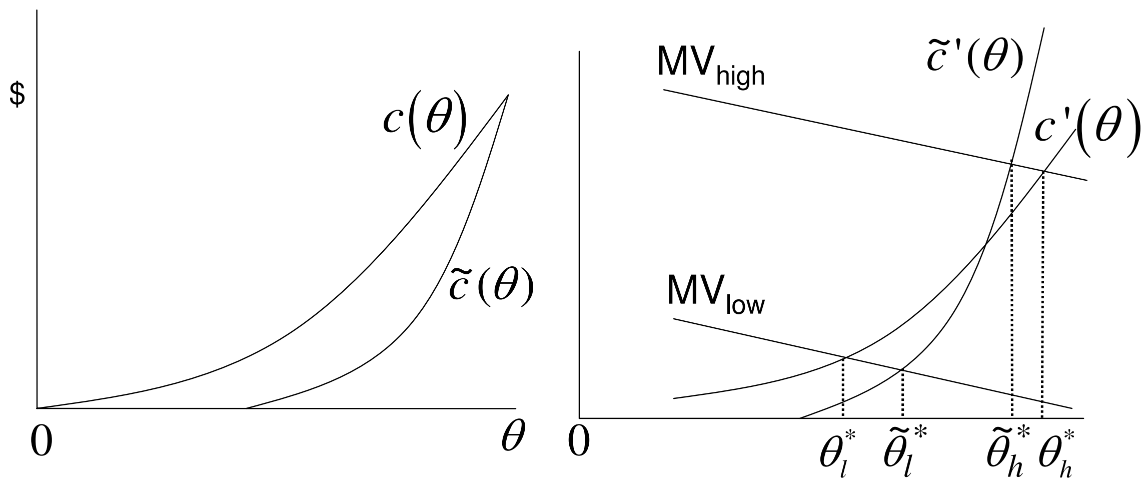

Figure 2: Impact of IAT

everywhere, i.e., for all $0 \leq \theta \leq 1$. Thus, all firms would choose a higher level of accuracy in the presence of DfD. Additionally, DfD is likely to impact the value function V through reducing the cost of recovery.

5 Conclusion and future research

This exploratory research on the impact of information for product recovery shows that the firm's response to a better information signal is highly dependent on the information structure of the signal. First, we show that the proportion of products that are recovered is non-monotonic in the accuracy of information – a firm may optimally recover either more or fewer goods as the quality of their signal increases. This has implications for policies aimed at increasing the usage of IAT. Second, we show that the value of IAT may not lay in collecting more information overall, but rather in making information collection more efficient. Since the optimal amount of information occurs at the point where the marginal benefit from additional information equals the marginal cost of collecting it, the key is how the new technology or design affects the cost of achieving a certain level of information. Overall, we have shown that it is not simply the amount of information that is important, but what exactly the information contains and the cost of retrieving it. Thus, it is important for analysts not to over-generalize results regarding the value of earlier or better information based on assuming a particular information structure. Future research is needed on the relation between the business environment and the value companies can reap from using data logging technology for product recovery management.

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6 Appendix

The most general definition of a more informative signal is based on the work of Bohnenblust, Shapley, and Sherman as referenced in Blackwell [2]. This definition says that a signal Y is more informative than a signal Y' if every decision maker is better off with signal Y. Blackwell has shown that this is equivalent to sufficiency [2, 3]. The problem with this definition is that it is very restrictive, in the sense that very few signals can be compared by this criteria. Since our problem has more structure, we can increase the generality of our definition, allowing many more signals to be compared.

A signal Y is more informative for the disposal/recover decision problem if it increases the value of (1) for all $V(\cdot)$ defined as above. Thus we can say Y is more informative than Y' if and only if

$$\Pr\left[Y \geq y^*\right] \mathrm{E}\left[V\left(\Gamma\right)|Y \geq y^*\right] > \Pr\left[Y' \geq y'^*\right] \mathrm{E}\left[V\left(\Gamma\right)|Y' \geq y'^*\right] \tag{3}$$

for all V. Note that

$$\begin{aligned}&\Pr\left[Y \geq y^*\right] \mathrm{E}\left[V\left(\Gamma\right)|Y \geq y^*\right] = \\ &\Pr\left[Y \geq y^*|\Gamma \geq \gamma^*\right] \mathrm{E}\left[V\left(\Gamma\right)|\Gamma \geq \gamma^*\right] + \Pr\left[Y \geq y^*|\Gamma < \gamma^*\right] \mathrm{E}\left[V\left(\Gamma\right)|\Gamma < \gamma^*\right]\end{aligned} \tag{4}$$

where $E\left[V\left(\Gamma\right)|\Gamma \geq \gamma^*\right] > 0$ and $E\left[V\left(\Gamma\right)|\Gamma < \gamma^*\right] < 0$. Therefore Y is more informative than Y' if and only if

$$\begin{aligned}&\Pr\left[Y \geq y^*|\Gamma \geq \gamma^*\right] \mathrm{E}\left[V\left(\Gamma\right)|\Gamma \geq \gamma^*\right] + \Pr\left[Y \geq y^*|\Gamma < \gamma^*\right] \mathrm{E}\left[V\left(\Gamma\right)|\Gamma < \gamma^*\right] \\ &\geq \Pr\left[Y' \geq y'^*|\Gamma \geq \gamma^*\right] \mathrm{E}\left[V\left(\Gamma\right)|\Gamma \geq \gamma^*\right] + \Pr\left[Y' \geq y'^*|\Gamma < \gamma^*\right] \mathrm{E}\left[V\left(\Gamma\right)|\Gamma < \gamma^*\right]\end{aligned} \tag{5}$$

for all V. This in turn is true if and only if

$$\Pr\left[Y \geq y^*|\Gamma \geq \gamma^*\right] \geq \Pr\left[Y' \geq y'^*|\Gamma \geq \gamma^*\right] \tag{6}$$

$$\Pr\left[Y \geq y^*|\Gamma < \gamma^*\right] \leq \Pr\left[Y' \geq y'^*|\Gamma < \gamma^*\right] \tag{7}$$

This is equivalent to a more sensitive (6) and more specific (7) test in medical terminology.

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