Remanufacturing/Refurbishment with RFID-generated Item-Level Information

Wei Zhou[1,3], and Selwyn Piramuthu[2,3]

[1]Information & Operations Management, ESCP Europe, Paris, France
[2]Information Systems and Operations Management, University of Florida
Gainesville, Florida 32611-7169, USA
[3]RFID European Lab, Paris, France.
wzhou@escpeurope.eu, selwyn@ufl.edu

Abstract. As an integral component of sustainable manufacturing, recycling and remanufacturing have been gaining popularity in line with Green initiatives. While the importance of item-level information their success has been stressed, the potential of RFID technology in recycling/remanufacturing has not received much attention in the research literature. We attempt to address this gap by considering RFID tags and their applications from a recycling/remanufacturing perspective and propose a knowledge-based framework to assist such process based on RFID-generated item-level information. Specifically, we consider quality improvement issues related to repair and refurbishment as well as end-of-life recycling issues from the perspective of item-level information generated through RFID tags.

1 Introduction

The increase in recent initiatives associated with green supply chains have spawned a plethora of related initiatives in the manufacturing sector. Specifically, recycling and remanufacturing have been identified as means to address some of the issues related to material wastage (e.g., Aras et al. 2006; Darnall et al. 2008). The process of remanufacturing include the collection of defective (due to manufacturing) and end-of-life products as well as manufacturing byproducts and re-engineering or reassembling of products back to new, as-new, or refurbished condition. While it is generally accepted that RFID tags provide cost-effective means to facilitate recycling and remanufacturing, existing published literature provide very little guidance in this regard.

Motivated by RFID's unprecedented characteristics of item-level auto-identification (e.g., Kohn et al. 2005; Zhou 2009), we propose an adaptive knowledge-based framework to utilize RFID-generated item-level information for product remanufacturing/refurbishment and illustrate its usefulness in this domain. We consider product remanufacturing process from a heuristic perspective with the goal of (1) reducing both environmental and economical waste, (2) improving manufacturing quality to decrease the rate of defects, (3) improving the efficiency of remanufacturing process, (4) facilitating product design and (5) enhancing Customer Relationship Management (CRM).

Specifically, we consider products that have manufacturing defects with missing or defective components, end-of-life used products that have some salvageable component parts in them and manufacturing byproduct into consideration. Most manufacturers treat remanufactured items that are put together using unused components from defective products as new and those that were used for a short period of time as refurbished. We restrict ourselves to considering only issues related to quality improvement from repair and refurbishment as well as end-of-life recycling process from the perspective of item-level information generated through RFID tags.

The remainder of this paper is organized as follows: we consider quality improvement of repair and refurbishment in Section 2 and develop a model to analyze the dynamic in this scenario. We then consider the end-of-life recycling process scenario in Section 3 with an example. We conclude the paper with a brief discussion in Section 4.

2 Quality Improvement of Repair & Refurbishment

Generally speaking, the process of repair and refurbishment in remanufacturing scenarios identify and replace parts from tested products that are found to be defective. By incorporating RFID-generated item-level information and its tracking/tracing capability for repair and refurbishment processes, it is possible to improve the overall quality of the resulting products. This is primarily due to the lower granularity of information that is generated through item-level RFID tags that enable the process to uniquely identify the specific characteristics of each of the product and tailor the best possible means to address any issues that are present.

Remanufacturing facilities generally keep inventory of both new parts and working parts that are taken from defective products. Consider a dysfunctional product, for example, with a defective component that needs to be replaced with a working component of the same specifications that is taken from another dysfunctional product. Traditionally, during the remanufacturing process, parts are randomly chosen to replace the defective ones. This process introduces variance in the remanufactured product quality due to uncertainties in quality of replacement component parts as well as in compatibility match. This variance is due to mismatch introduced by the randomness present in the process.

For illustration purposes, assume that we have five parts to fit the dysfunctional product mentioned above and that the key specification of these parts is represented by $\{10, 9.8, 10.2, 8, 12\}$. As a result of compatibility issues, the normalized quality of the possible resulting product is $\{5, 4.3, 4, 2, 1\}$. Without the use of RFID-generated item-level information, the average quality of this remanufactured product is 3.26 with a standard deviation of 1.68. However, with the use of RFID-generated item-level information, the quality of this product is 5 with certainty due to specifically tailoring the processes to address identified deficiencies that are specific to each product.

The beneficial properties present in this scenario is multiplied when there are multiple products are simultaneously processed. If we have two dysfunctional products with similar defective components, the normalized resulting quality from replacing the five available parts for these two products (say) are $\{5, 4.3, 4, 2, 1\}$ and $\{3.2, 5, 4.5, 3.2, 2.9\}$. The average quality for the second product is 3.76 with a standard deviation of 0.93. The overall average quality of these products is invariably low. However, with the use of RFID-generated item-level information, the quality of both remanufactured products reach their maximum possible value of 5 simply because of the targeted focus in identifying issues and addressing those with the most appropriate response.

2.1 Model & Analysis

In general, factory restored products are usually characterized by a high degree of uncertainty with respect to their quality primarily due to variances in quality control and unobservable history of the components within. With RFID-generated item-level visibility, it is possible to identify the components uniquely as well as their specifications at the item level. Moreover, traditionally, components are labeled as qualified if they pass certain quality tests. Consider a repair task with a need to replace $m-1$ components when there are m components in total $\{\mathit{\Gamma}|\mathit{\Gamma}_1, \mathit{\Gamma}_2 \cdots \mathit{\Gamma}_m\}$ including the primary component. Each component $\mathit{\Gamma}_i$ has n_i items $\{\mathit{\Gamma}_i|\gamma_{i1}, \gamma_{i2}, \gamma_{i3} \cdots \gamma_{in_i}\}$ that have all passed the quality test. $\{\mathit{\Gamma}|\mathit{\Gamma}_1, \mathit{\Gamma}_2 \cdots \mathit{\Gamma}_m\}$ follow joint distribution $f_{\mathit{\Gamma}_1, \mathit{\Gamma}_2 \cdots \mathit{\Gamma}_m}$. Then with production function $g(\cdot)$, we can characterize the output $Y = g(\mathit{\Gamma}_1, \mathit{\Gamma}_2 \cdots \mathit{\Gamma}_m)$ in

its cumulative density function as:
$F_y(y) = \int\int\cdots\int_{g(\varGamma_1,\varGamma_2\cdots\varGamma_m)\leq y} f_{\varGamma_1,\varGamma_2\cdots\varGamma_m}(\varGamma_1,\varGamma_2\cdots\varGamma_m)d\varGamma_1,d\varGamma_2\cdots d\varGamma_m$

In the ideal scenario where RFID-generated item-level information can be effectively used to address issues, the quality improvement of refurbished products is given by:

$$\varDelta_Q = max\{Y\} - E[Y] \tag{1}$$

Since Y takes $N : \{N = n_1 \cdot n_2 \cdots n_m\}$ different possible values, the distribution of $max\{Y\}$ follows: $f^y_N(y) = Nf(y)F(y)^{N-1}$. Therefore $\varDelta_Q$ becomes:

$$\varDelta_Q = \int_y (Nu^{N-1} - 1)yu'dy \tag{2}$$

where

$$u = F_y(y) \tag{3}$$

If there are k products with multiple defects that need to go through the same repair procedure, the distribution of $max\{Y\}_k$ is

$$f^y_{k:N}(y) = \frac{N!}{(k-1)!(N-k)!}u^{k-1}(1-u)^{N-k}f_y(y)$$

And the total quality improvement for all these k refurbished products becomes:

$$\begin{aligned} \varDelta_Q &= \sum_{i=1}^{k} (E[y_{i:n}] - E[y]) && (4) \\ &= \int_y (NF_{binomial(N-1,u)}(k) - k) \cdot yf_y(y)dy && (5) \end{aligned}$$

If the production itself is stable, the quality improvement $\varDelta_Q$ therefore would depend mostly on the uncertainty from the input $\delta(\varGamma)$. Since we have more control over the process when low granularity information at the item-level is used, we can clearly see that this leads to improvement in the quality of the resulting products.

3 EOL Recycling Process Optimization

A relatively large portion of end-of-life (EOL) products go into their last mile of recycling before they are decomposed into simple formats such as simple chemical compounds. This stage of recycling usually involves using very brutal forces such as grinding, burning, chemical eroding which produce a large amount of waste and pollution. The ultimate goal of close-loop or green supply chain is to minimize the size of this recycling process that nevertheless seems unavoidable in any industry.

Traditionally, EOL products at this stage are pre-sorted in order to go through several different recycling processes. The sorting preparation is normally not very accurate because of the size of operation as well as the cost. As a result, more pollution is generated when the EOL products go through a wrong recycling process (Figure 1). For example, any material made up of potentially harmful chemicals when burned (even if by mistake) releases harmful particulate matter into the environment.

With RFID tagging, the sorting process and the following recycling processes can be operated more accurately. As a result, the unnecessary pollution caused by mis-operation can be minimized. The actual effects of using RFID in recycling process however depend on several major factors, including the degree of randomness during the sorting process and the severity of consequences due to mis-operation.

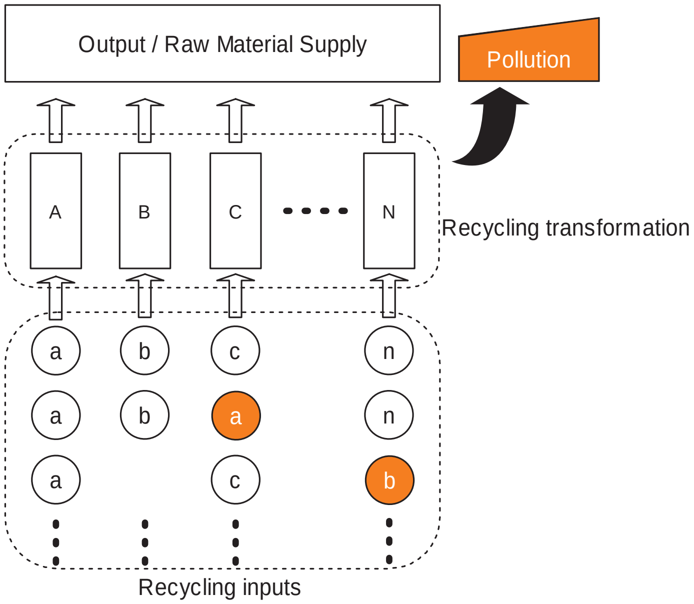

Fig. 1. Recycling process with mis-matched products

For example, consider n different recycling processes in a recycling plant that map the transformational operations of the n different categories of EOL inputs X. In a typical scenario, each input item goes through its corresponding process and produces an amount of valuable output Y as raw material for remanufacturing as well as a certain amount of pollution Z, such that

$$\{Y, Z\}_i = f_i(X) \tag{6}$$

However, if the input is produced by a wrong process, an additional amount of pollution is generated resulting in the loss of valuable output.

$$Z_{ij} = g_{ij}(X_i) \tag{7}$$

where i indicates the input category and j indicates the recycling procedure. The set of G forms a recycling transformation matrix that represents all possible outcomes. For an example scenario with two kinds of input, the transformation function matrix can be represented as:

$$G_{2\times 2} = \begin{bmatrix} f_1 & g_{12} \\ g_{21} & f_2 \end{bmatrix}$$

With item-level RFID-tagging, the system generates perfectly transparent information and in a perfect operational scenario, and the output is given by

$$\{Y, Z\}_{RFID} = \sum_{\forall X_i \in X} \sum_{i=1}^{n} f_i(X_i) \tag{8}$$

Without sufficient tracking and monitoring tools, the output becomes

$$\{Y, Z\}_{NON} = \sum_{\forall X_i \in X} \sum_{i=1}^{n} \sum_{j=1}^{n} [f_i(X_i)\delta(i, j) + g_{ij}(X_i)(1 - \delta(i, j))] \tag{9}$$

where the incidence function $\delta(i, j) = 1$ if $i = j$ and $\delta(i, j) = 0$ otherwise.

The difference between equation 8 and equation 9 represents the benefit, which is indeed the effect when the item and recycling process don't match ($i \neq j$). It can be written as

$$\varDelta_R = \sum_{\forall X_i \in X} \sum_{i=1}^{n} \sum_{j=1}^{n} \left[f_i(X_i) + g_{ij}(X_i) \right] \left(1 - \delta(i,j)\right) \tag{10}$$

Equation 10 indicates that the potential benefits of utilizing RFID at the recycling stage of remanufacturing depends on three factors: the value transformation $f_i(\cdot)$, the pollution factors $g_{ij}(\cdot)$, and the dynamics of input $\delta(\cdot)$. These expressions provide us an estimate and guideline on the benefit to expect with item-level information generated through RFID tags.

4 Discussion

As green initiatives expand to more domains, it is important to critically examine processes that could be improved to those that result in less wastage. This is especially true in manufacturing where remanufacturing and recycling can be used to reduce wastage as well as improve the effectiveness of usage of constrained resources. We considered a practical problem with respect to dynamically adjusting manufacturing/remanufacturing process through use of RFID-generated item-level information. This process can be automated and operationalized in a seamless fashion through RFID-embedded component tags on individual parts. These RFID-tagged manufacturing parts also enable the quality manager to continually adjust manufacturing parameters at the item-level as is deemed necessary to improve the overall quality of the finished products.

In general, in a closed-loop supply chain (e.g., Fleischmann et al. 2003), RFID could possibly be beneficial for: (1) Improved manufacturing quality and reduced waste; (2) More efficient remanufacturing process (optimized diagnosis and reduced cost); (3) Improved quality of remanufactured products; (4) Reduced pollution in recycling / decomposition. The level of operational uncertainty plays a critically important role to evaluate an RFID project for remanufacturing. We modeled two scenarios and developed expressions that illustrate the benefits that could be obtained through item-level RFID-tagging and the appropriate use of the information generated in the process.

References

1. Aras, N., V. Verter, T. Boyaci. 2006. Coordination and priority decisions in hybrid manufacturing/remanufacturing systems. Production Operations Management, 15, 528-543.
2. Darnall, N., G. J. Jolley, R. Handfield. 2008. Environmental management systems & green supply chain management: Complements for sustainability? Business Strategy & Environment, 17(1), 30-45.
3. Fleischmann, M., J. van Nunen, B. Gre. 2003. Integrating closed-loop supply chains and spare-parts management at IBM. Interfaces, 33, 44-56.
4. Kohn, W., V. Brayman, J. Littleton. 2005. Repair-control of enterprise systems using RFID sensory data. IIE Transactions, 37(4), 281-290.
5. Zhou, W. 2009. RFID and item-level information visibility. European Journal of Operational Research. 198(1), 252-258.