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Improving Product Recovery Decisions through Enhanced Product Information

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Abstract
The advent of networked RFID-based automated identification approaches has resulted in the ability to enhance the quality of product information that is available to make decisions along the product lifecycle. One of the major impact areas of such a capability is in improving the effectiveness of decisions made during endof- life product recovery. This paper investigates the link between product recovery decisions and information quality through observations made from a number of case studies. A Bayesian approach for quantitative evaluation of the impact of enhanced product information on product recovery option decisions is also presented.

1. Introduction

Due to environmental legislations, continually increasing landfill costs, and realisation of cost benefits arising from effective product recovery management, manufacturers have started considering new technologies to manage returned and obsolete products in an efficient manner. Unlike conventional manufacturing and assembly processes, demanufacturing and disassembly operations are characterised by a high variety of products, uncertain product condition after usage, and a not so rigidly defined process goal [1].

As a result of such uncertainties associated with returned products, effective recovery of value from these products requires extensive information about the identity and the condition of the product when it is returned. However, product information shortage is widely blamed in the literature as one of the major obstacles for efficient recovery of value from returned products [2]. This problem becomes critical as government regulations require manufacturers to share information that would facilitate product recovery with remanufacturers and recyclers. The concept of the so-called ‘networked RFID’ [3] developed by the Auto-ID Centre [4] makes it possible for a product to carry complete information associated with it throughout its lifecycle and ensure flow of this information between the various actors in the supply chain, for e.g., between the manufacturer and the recycler.

To find out the exact requirements on the type and quality of information that is demanded by decisions made during product recovery, a case study exercise that covered nine remanufacturing and recycling facilities was undertaken by the authors. The case studies examined the various decisions involved while recovering end-of-life (or returned) products, their relationship and dependency on the type and quality of information associated with the product with an aim to evaluate the impact of RFID-based product identification technologies on the performance of product recovery operations.

The ultimate objective of this research is to test and prove the hypothesis that the ready (or timely) availability of complete and accurate information associated with a product will lead to a significant increase in the effectiveness of product recovery decisions, in particular the decision about the best recovery option to be chosen for a given product, which in turn will result in improved performance of product recovery operations, measured by performance measures such as net profit generated and percentage of the product reused.

The next section will use observations from the case study exercise as a basis for understanding how product recovery decisions are made and the information requirements for making these decisions, and identify the link between product recovery decision effectiveness and key information quality parameters. Having identified the information quality requirements imposed by product recovery decisions, in section 3 we will propose a networked RFID-based approach to manage and deliver enhanced product information. Acknowledging the fact that enhancing product information comes with a cost attached to it, in section 4 we propose an approach to quantify the impact of enhanced product information on product recovery decisions. Finally, section 5 provides some concluding remarks.

2. Case Studies

2.1 Overview of companies

As discussed, this study involves nine remanufacturing/recycling companies. In particular, the case studies concentrated on companies that were involved in the recovery of electric and electronic products. This was influenced by two major factors:

- government regulations on waste electric and electronic equipment [5], and
- the fact that electric and electronic equipment are most suitable for reuse and remanufacturing due to their long wear-out life and short usage period [6].

Seven out of the nine companies visited during the course of this case study dealt with brown goods, and two were white goods remanufacturers. The information presented in this paper has been collated from semi-structured interviews with company personnel ranging from top-level executives to factory floor managers, and also from observations made during on-site visits.

2.2 Product recovery operations

In this section, we will extract the common features found in the different companies and present a general picture of how product recovery is performed in the industry. Figure 1 shows the typical steps that are performed during product recovery.

Book-in

The first thing that is done when products come in through the remanufacturing shop floor is to book-in all the products into the company's inventory database. Essentially, this consists of noting the product type (for e.g., laptop, printer, mobile phone), and in some cases, the brand and model of the product as well.

Pre-sorting

After the products are booked-in, a preliminary sorting is performed on the products to filter out the products that do not apparently have much market value. This is the first decision point where there are three options available to the decision-maker:

- *reuse* — if the product is perceived to be of a value less than the cost incurred for further inspection and testing, but can be sold "as seen" in the market at a lower price;
- *recycle*, — if the product is 'evidently' bad or perceived to have no market demand; or
- *inspect and test* — if the product is perceived to be valuable enough to warrant further inspection and testing before a recovery decision is made. There is an underlying assumption that due to regulatory requirements, no products are landfilled directly.

Identification & Testing

If a product is deemed to be valuable enough to warrant further inspection and testing, additional efforts are put in to gather the information required to choose the recovery option that would maximise the value recovered from the returned product. This involves inspecting the product to gather its technical specification as well testing it to ascertain its physical and functional condition.

Grading

After the product has undergone thorough inspection and testing, a final decision about the choice of recovery option is made at this point. Here, in addition to the options available at the pre-sorting stage, depending on the quality and condition of the product, it could also be

- *reused* — if it is in good condition and there is a demand for it in the market,
- *refurbished* — if a market can be found with minor modifications or parts replacement, or
- *cannibalised for parts* — if the product does not have a market value as a whole, but has valuable components that can be retrieved and sold or used in refurbished products.

In the next section, we will look at the information required to make these decisions and also see how this information is collected.

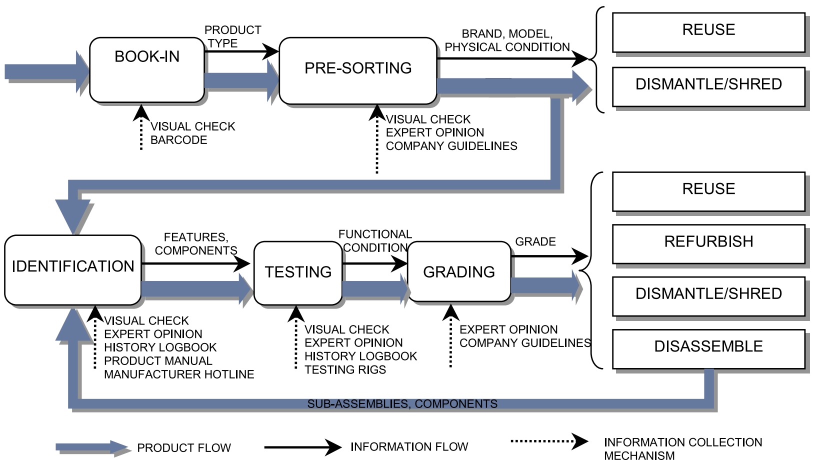

Fig. 1: Product recovery operations

2.3 Product information requirements and availability

In this section, we will look at the two decision points identified previously, namely the pre-sorting decision and the final product recovery option decision, and try to understand the level of information availability under which these decisions are made. We will also look at the various mechanisms that are used to collect the information associated with the products.

Information requirements for the pre-sorting decision

The pre-sorting decision is mainly made on a minimum system requirement basis, (for e.g., computers above Pentium 550 MHz will be sent for inspection and testing) which is obtained from the guidelines provided by the sales department (which makes this decision on the basis of the market situation). It is assumed that anything below this specification is not worth testing as it would not be costeffective to do so.

However, at this stage, only an external visual check is conducted, and the only information about the product that is known is the type, manufacturer, brand, and the model, if any.

One should keep in mind that in some cases such as mass-customised products like computers, the components of the system could vary widely within the same model, or the product could have undergone changes during its use (for e.g. replacement/ upgrade of parts), but that level of detail is not captured at this stage. Products are identified using various methods such as the manufacturer's barcode, manuals and specifications attached to the product, or in many cases, expert knowledge of the people handling the products (refer to Figure 1 and Figure 2).

When the remanufacturer receives a product that he has not seen before, for e.g., a new product such as a digital photocopier, they are quarantined and expert opinion (sometimes from outside the company) is sought to identify them. This causes a costly delay in processing the products and the issue of invoices. The delay in identification of the product, or even worse, misidentification of the product affects the marketability of the product.

Evidently, the pre-sorting decision is made with limited/ inaccurate information, and therefore affects the effectiveness of the decision made. As an outcome, often low quality products are sent for inspection and testing, thereby decreasing the overall cost-efficiency of the process. It is also possible that many good products are sold at a price lower than its value, or even sent for recycling, thereby losing an opportunity to maximise profits.

Information requirements for the final grading decision

The products that make the 'first cut' go through detailed inspection and testing. To optimise the product recovery option decision, it is necessary to ascertain the complete identity and condition of the product. By "identity", we mean all the information that is required to completely describe the product (for e.g., technical specifications, components etc.).

In companies where the primary objective is to recycle the product, it is required to know what the constituent materials are so that appropriate separation and purification techniques can be applied. Environmental regulations also stipulate that certain hazardous substances have to be separated first (for e.g., batteries) before the product can be shredded.

This information can be collected by way of contacting the manufacturer, by consulting the product manual and the maintenance logbook (if available), or by detailed inspection of the product. Direct access to the manufacturer is limited to third-party remanufacturing companies, or in the case of a closed-loop supply chain where this information maybe readily available. Figure 2 shows the distribution of various product identification methods used by the companies that participated in the case studies.

The maintenance logbook is an important source of information for products that undergo a lot of maintenance and parts replacement throughout their life. However, in most cases it was seen that the logbooks are not kept upto- date, and hence the information obtained is inaccurate. For certain products such as computers, identification of the product and their components can be performed by running a program that scans the system for their components and features (for e.g., PC Check).

Making a decision whether the product is to be re-used, refurbished, cannibalised for parts, or recycled requires more than just knowing the identity of the product. The residual value of the product depends on various quality parameters such as the age, functional condition (working, or not working), physical condition, functional age (as a measure of obsoleteness), remaining useful life, etc.

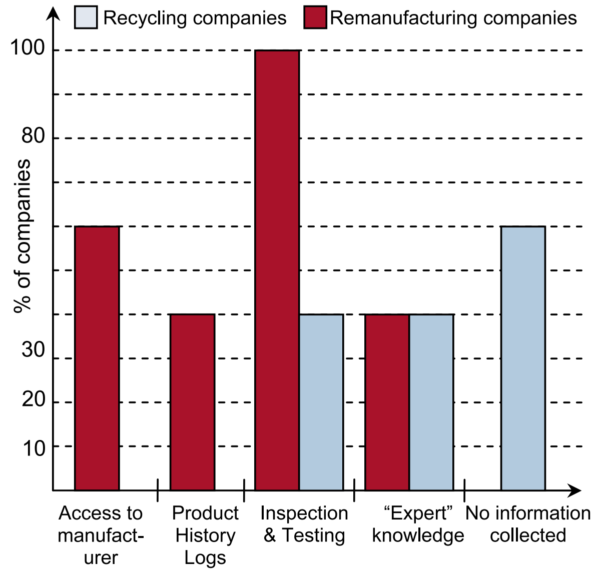

Fig. 2: Product identification method used

The value of these parameters, which define the current state of the product, are determined through testing or estimated from knowledge gathered through experience. In the case of computers, identification and preliminary testing can be performed at a single step, as the product-scanning programs mentioned earlier will also identify nonfunctioning components. Nevertheless, this program will not be able to identify the exact type of fault in a component, and hence further diagnosis will be required to be performed to ascertain that.

If we examine Figure 2 closely, we can see that the companies that remanufacture or refurbish most of the incoming products are those that have more access to product information, such as access to manufacturer databases or history logbooks. Due to shortage of information available, rest of the companies end up recycling most of the products in spite of knowing that refurbishment or reuse will bring higher profits to their operations. Having understood the importance that the availability of information plays in product recovery operations, in the next section we will examine how the decisions made during product recovery are affected by the quality of information that is available to the decisionmaker.

2.4 Linking product recovery decisions to information quality

In this section, we will identify the key information quality parameters that are critical for making effective product recovery decisions, so as to understand the requirements to be met by an information system that supports these decisions.

From the above discussion, clearly the availability of complete product information plays a very crucial role in the effectiveness of decisions made during product recovery. The fact that each product is subjected to a different set of conditions throughout their lifecycle means that this information will be unique to every single product.

By observing how product recovery decisions are made and how the information required to make these decisions is collected by the remanufacturers, it can be understood that it is not merely the "completeness" of information that is the critical issue here. The information required for making product recovery decisions "can" be collected by performing extensive inspection and testing. This being labour intensive and very expensive, in most cases is not economically justifiable due to the low-value nature of returned products, resulting in only those products that are evidently valuable on the outset being recovered efficiently. Hence, it is the absence of 'readily available' or 'timely' information that is the biggest hindrance to making effective decisions.

Timely availability of information is also important due to the volatility in the market value of returned products. Figure 3 shows how the market value of a P3 650MHz laptop deteriorates with time. The data used for this plot was obtained from one of the companies involved in the case study. This verifies the observation made in Blackburn et al. [7] that the value of volatile products like computers and laptops deteriorates at the rate of more than 1% per week and that the rate increases as the product nears the end of its lifecycle. Given the fact that remanufacturing companies often hold around 6-7 weeks worth of inventory, the products lose nearly 10% of their value between the time the remanufacturer receives the product and the time they sell it.

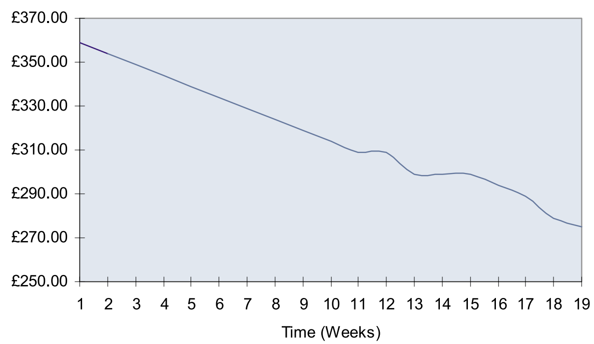

Fig. 3: Value depreciation of a 650MHz laptop

Moreover, some of the contracts between manufacturing companies and their 3rd party operators) stipulate a maximum threshold period before which the remanufacturer has to sell the products. If the remanufacturer is not able to sell it within that stipulated time, the product will have to be bought from the manufacturer at a previously arranged price, which in most cases would be more than what the remanufacturer would be able to sell for in the secondary market due to rapidly declining prices. Hence, it is clear that the ability to collect complete information about the product is not just sufficient—it is necessary to be able to collect this information in a timely manner.

Summarising, it is desirable that product information that supports product recovery should have the following qualities:

- *Unique identification*—to enable individual information trails for each unique object throughout its lifecycle and across the whole supply chain.
- *Ready availability (or timeliness)*—to ensure that information is readily available for decision-making and execution process with minimal need for manual inspection or testing.
- *Completeness*—to ensure that all relevant information is available for optimising decisions.
- *Accuracy*—to reduce or eliminate inaccurate representations of current and historical product information.

In the next section, we will look at how the concept of networked RFID supported can ensure the quality of information that is required by product recovery decisions.

3. A Delivery Mechanism for Enhanced Product Information — Networked RFID

Radio-Frequency Identification (RFID) is a technology which allows remote interrogation of objects using radio waves to read data from RFID tags which are at some distance from an RFID reader. This has several advantages over manual scanning using optical barcodes, since many tagged items (or embedded sub-components of a composite product) could be simultaneously identified in an automated manner, very quickly and without the need for line-of-sight to each item.

A recent breakthrough in enabling affordable widespread global deployment of RFID is the emergence of the socalled 'EPC Network' as a means of connecting a product tagged with an RFID to a network. After discussing the key technology components of the EPC network, we will discuss how RFID-based product identification technologies can improve product recovery decisions.

3.1 An overview of the EPC Network

In this section we will provide a brief overview of the EPC network developed by the Auto-ID centre. For a detailed discussion of the EPC network and its applications in product lifecycle management, the reader is referred to Harrison et al. [3].

In order to achieve a networked RFID solution that satisfies the requirements for making effective product recovery decisions, the EPC Network consists of the following fundamental technology components, which work together to bring about the vision of being able to identify any object anywhere automatically and uniquely. These are:

- A Unique product identifier (*Electronic Product Code*);
- *Radio Frequency* tags and readers to ensure timely and automatic identification of product.
- A distributed product information database (The *EPC Information Service*) linked to an information lookup service (The Object Name Service) to ensure completeness and accuracy of product information.

The Electronic Product Code (EPC)

The aim of the EPC [3] is to provide a unique identifier for each object. Designed from the outset for scalability and use with networked information systems, the EPC typically consists of three ranges of binary digits (bits) representing (refer to Figure 4): a. an EPC Manager (often the manufacturer company ID) b. an object class (usually the product line or SKU) and c. a unique serial number for each instance of a product.

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21.203D2A9.16E8B8.719BA3OC3
Version  Manufacturer  Product Type  Serial Number
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Figure 4: Electronic Product Code

Thus, EPC introduces mass-serialisation, giving each instance of a product a unique identity and allowing information systems to store accurate, complete and relevant individual data (an individual life history) of each unique object.

Radio frequency tags and readers

Radio Frequency Identification (RFID) is a key technology enabling automatic reading of multiple items simultaneously, without requiring manual scanning of each individual item. The reader emits radio waves of a particular frequency. When the tags enter the range of a reader, their antenna absorb energy from the radio field, powering the microchip which stores the unique EPC identity code — and returning this information back to the reader via a modulation of the radio waves. Thus, RFID technology provides the ability for automated and efficient method for collecting product information in a timely and accurate manner.

The Object Naming Service (ONS)

The Object Name Service (ONS) is used to convert an EPC into a number of internet addresses where further information about a given object may be found.

Recognising that the remanufacturer may require information about the product as it moves through its lifecycle, and that this information may be held by various parties along the supply chain, the ONS will provide the serial-level lookup for instances of a given product, pointing to the various other parties across the supply chain, which also hold information.

The EPC Information Service (EPCIS)

The EPC Information Service [5] allows trading partners to access and exchange data through a standard interface, while interfacing the back-end to diverse databases and information systems from multiple vendors, without their partner needing to know the details or have direct access to the underlying systems. Such a distributed database tied with an ONS registry that provides pointers to all the EPC Information Services on the individual supply chain followed by each individual object in a more robust manner would help in collecting and retrieving complete lifecycle information associated with a product.

The EPC Network

These elements together form the core infrastructure of the EPC Network and provide the potential for automatic and unique identification of any tagged product. Figure 5 shows how information about the toaster is stored in a distributed manner in various EPCISs across its lifecycle.

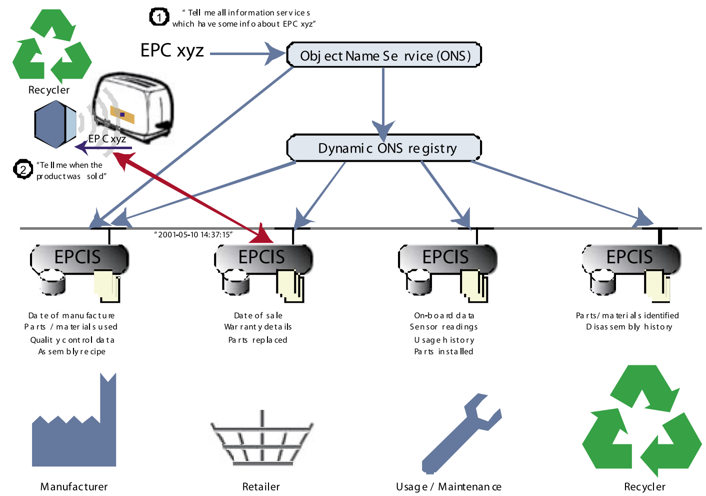

Figure 5: Retrieving product information through the EPC Network

It also describes clearly how, a recycler could find the toaster's date of sale (possibly to find out how long it has been used). The RF reader detects the presence of the toaster when the toaster returns its EPC code in response to the reader's interrogation. The software application connected to the RF reader will then query the ONS to obtain the location of EPCISs that contains data linked to the EPC code of the toaster. It can then query the retailer's EPCIS to obtain the date of sale. Without a product-oriented information system similar to the one provided by the EPC network, it might be impossible for the recycler to obtain that kind of information.

3.2 The role of networked RFID in product recovery

As seen in the previous section, tagging individual products using RFID will provide an automated means of capturing information about the product. We have seen that in many cases, the product identity is misinterpreted and wrong decisions are made. Apparently, automatic product identification enabled by networked RFID would eliminate these errors by providing complete and accurate information about the identity of the product, and by automating the booking-in process, thereby making it more efficient and less error-prone. Moreover, by enabling ready availability of product information through networked databases linked to the product, it is possible to gather complete identity information during book-in, thereby eliminating the need for further manual identification. As networked RFID would enable ready availability of complete lifecycle information about the product, the decisions made at this point are far better informed than how it is done currently.

In addition, it is also possible to monitor critical performance parameters of the product (temperature, number of revolutions, etc.) throughout its life by attaching sensors that record crucial lifecycle data and by linking these sensors to the RFID tag, it is possible to make this information available at the identification step itself. The use of such devices has been discussed elsewhere in the literature [8]. This helps the decision-maker to filter the products going to the testing process, or make early assumptions on the cost of repair/refurbishment, so as to optimise the performance of the whole operation. In the case where the product is to be recycled, this would alert the recycler about potential hazardous substances in the product, and help identify the products that require special processing.

3.3 RFID Vs Traditional methods

As we saw in section 2.3, two methods are found to be used in the industry to gather information associated with returned products:

- Manual (visual) inspection—where the products are visually inspected and identified; and
- Barcodes—where the product can be identified by scanning a barcode attached to it and obtaining associated information from a database linked to the serial number represented by the barcode.

Figure 6 presents a comparison between these two methods and RFID-based product identification. In the manual approach, very little information is collected during the book-in stage, and detailed inspection and testing is required to gather information about the product. When barcodes are used to identify the product, the serial number can be used to access the manufacturer's database and identify the product and its original specifications. However, information about any changes to the product after the point-of-sale has to be collected by disassembling the product and inspecting its internal parts as most barcodes identify only the product-type and do not identify products at the item-level.

On the other hand, if the product and its major components are tagged with RFID, information about its current specification can be obtained without disassembling the product as RFID tags can be read without line-of-sight. As discussed earlier, with a networked RFID approach to lifecycle information management, information such as the age of the product (determined by its date of sale, as obtained from the retailer's EPCIS), and its usage rates (obtained either by using sensors to monitor crucial lifecycle data, or by connecting to maintenance EPCISs where history logs can be accessed) can also be obtained at the book-in stage itself, thereby eliminating the need for detailed inspection. Although such an approach would provide pointers to the product's residual life, the actual functional condition of the product will still have to be determined by testing the product.

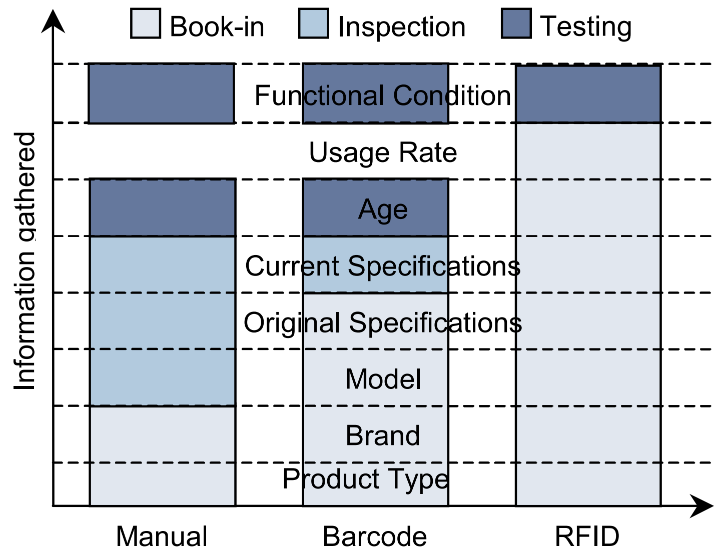

Fig. 6: Product data collection locations

From the above discussions, it is clear that RFID can bring two-fold benefits to product recovery operations:

- process improvements—brought about by automating the product identification process, and
- decision improvements – brought about by enhancing the quality of information available to the decision-maker.

However, such enhanced information comes with a cost attached to it. In order to understand the costeffectiveness of using such technologies, in the next section we will investigate means to quantify the impact of enhancing the quality of information available during product recovery.

4. Towards Quantifiying the Impact of Enhanced Information on Product Recovery Decisions

In this section, we will propose a novel method to model product recovery decisions as a means for quantitative evaluation of the relationship between product information quality and product recovery decision effectiveness.

4.1 Characteristics of product recovery decisions

The primary role of product information in product recovery decision situations is to reduce to the level of uncertainty that prevails in those situations (in fact, this holds true for every "information-decision" relationship). As discussed before, tagging a product with RFID would enable timely availability of information that is directly associated with a product, i.e., information that would enhance the decision-maker's knowledge about the *current state* of the product. Hence, in this analysis we are concerned with investigating how the reduction of structural and quality uncertainty associated with returned products would affect the performance of product recovery operations.

The case studies showed that the identity of a product is normally revealed in a series of information gathering steps (presorting, inspection, testing, etc.). Hence, even though limited information is available at the beginning of the process, recovery decisions are often made after collecting more information. Therefore, this is a situation where decisions are often made after assessing "new information" that becomes available through different information gathering methods.

From the case studies it was also clear that in addition to the availability of product information, the ability to retrieve this information in a timely manner is critical to making effective product recovery decisions, as the net benefit from recovering the product decreases with the time taken to collect enough information to make the decision.

4.2 A Bayesian approach for analysing product recovery decisions

In this section, we propose the use of a Bayesian decision theory approach to analyse the effect of enhanced information on product recovery decisions.

Decision-making under uncertainty

A well-known rule for making decisions about taking a particular action given alternative uncertain outcomes is the 'principle of maximum expected utility' (MEU). The MEU principle dictates that we should take actions that maximise the value computed by summing together the value attributed to each possible outcome multiplied by the probability of that outcome [9]. In mathematical terms, if *H* is a set of n possible states of the product, *D* a set of feasible product recovery decisions, then the utility of making a decision D_j (for e.g., this could be the selling price, if the decision is to reuse the product) when the state of the product is H_i is represented by a mapping U_k: $H_i \times D_j \rightarrow u(H_i, D_j)$. Then, the expected utility of an action/decision D_j, given some background information about the product # is given by:

$$EU(D_j) = \sum_{i=1}^{n} p(H_i \mid \xi)\, u(H_i, D_j) \qquad (1)$$

The best decision, D^*, is the action with the greatest expected utility, given the probability (belief) distribution and the utility model, and is given by:

$$D^* = \arg\max_{D_j} \sum_{i=1}^{n} p(H_i \mid \xi)\, u(H_i, D_j) \qquad (2)$$

The maximum expected utility is thus given by:

$$\max_{D_j} \sum_{i=1}^{n} p(H_i \mid \xi)\, u(H_i, D_j) \qquad (3)$$

Equation (3) gives the maximum expected utility of making an immediate decision, given prior information. In the next section, we will see how the decision maker will evaluate her options if we give her the option to collect more information before making a decision.

Computing the value of information

Equation 3 gives the best decision to make under prior beliefs with prior information. If the decision-maker is often offered the ability to obtain more information (or evidences), say by conducting a test, and she would wish to know the value of the information provided by the test in order to decide whether it is worth going for the test or not. Such a situation occurs at the pre-sorting stage in the remanufacturing process where a preliminary evaluation is performed on the returned products and depending on the estimated value, a decision is taken as to whether further inspection and testing should be performed. In fact, each inspection/testing step in a remanufacturing process can be considered as an information collection process, and a decision about the recovery option for the product can be made after collecting one or more pieces of information. Now let us assume that the decision-maker has the option to perform a test τ, which will reveal the value of an evidence E_k. We shall use E_k^l to represent the value of this evidence, where *l* indexes outcomes of the test or observation. We denote the values of E_k, by $E_k^1 \dots E_k^m$, where *m* is the number of mutually exclusive values.

We can compute the expected value of information of performing the test by conditioning the probability of different states of the product on different outcomes of the test, and determining the expected value of the best actions associated with the revised probability distributions $p(H|E^l_{k,}\xi)$ using Bayes theorem. The expected utility associated with each test outcome then is weighed by the probability of that outcome, $p(E^l_{k,}\xi)$. Therefore the expected utility of making a decision after conducting the test is given by

$$EU(\tau) = \sum_{l=1}^{m} p\left(E_k^l \mid \xi\right)\left[\max_{D_j} \sum_{i=1}^{n} p\left(H_i \mid E_k^l, \xi\right) u\left(H_i, D_j\right)\right] \quad (4)$$

Then, we calculate the difference between the expected utility of actions, dictated by the current state of information and the expected utility of making the decision to act after performing the test. Thus, the expected value of information (conducting the test) is:

$$EVI(\tau) = \sum_{l=1}^{m} p\left(E_k^l \mid \xi\right)\left[\max_{D_j} \sum_{i=1}^{n} p\left(H_i \mid E_k^l, \xi\right) u\left(H_i, D_j\right)\right] - \max_{D_j} \sum_{i=1}^{n} p\left(H_i \mid \xi\right) u\left(H_i, D_j\right) \quad (5)$$

In equation 5, we have not considered the cost incurred in conducting the test, or collecting information. It should be kept in mind that information can be collected using various methods, each with a different cost structure. Equation 5 will give the "gross value" of the information to the decision-maker, and enables her to decide the type of system that is best suited to collect the required information, given the benefit arising from it. This is particularly useful in this research, as we are comparing different information methods (RFID vs. traditional methods).

Let us take a particular example, say a laptop with four different components of interest (1- hard disk, 2- processor, 3- CD drive, and 4- network card). Figure 7 shows the results of sensitivity analysis conducted on the product recovery decision model for this example built using the Bayesian approach detailed above. The figure shows the relationship between the value of information and probability of the product being good $p(H)$.

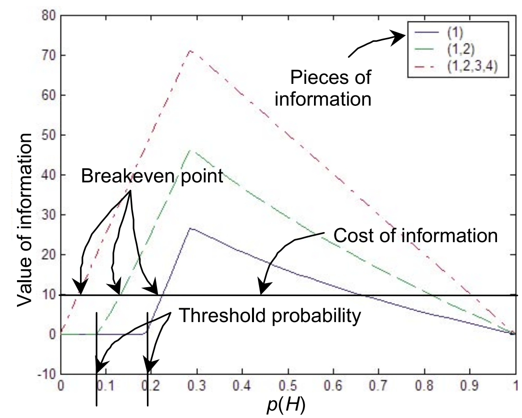

Fig. 7: The effect of information completeness

The different plots in the figure correspond to (1) — value of information associated with component 1, i.e., the size of the hard disk, (1, 2) — value of information associated with components 1 and 2, and so on. It was seen from the case studies that the probability of the product being good, i.e., the product quality varies with respect to the type of returns, the source of returns, as well as the type of business model used. From the figure, it can be seen that the value of information for products with very low as well as very high quality is low. In fact, below a threshold probability, information does not have any value at all. However, it can be seen that as increasing amounts of information becomes available, the value of information increases and the threshold probability decreases, and even for products with a low and high quality, there is some value for the information.

The horizontal line shows the cost of collecting information. The region between the points where the value of information curve meets the cost of information line gives the range of probabilities where availability of product information brings benefits to product recovery decisions. Assuming that the cost of information collection remains the same, the figure shows that if increasing amounts of information is made available, more products will start seeing benefits due to better decisions.

The effect of information timeliness in decision-making

The utility of making any recovery decision decreases with time due to two reasons:

- market value depreciation, which is a function of the product's value volatility, and
- the costs involved in conducting tests to retrieve information about the product.

We can adapt the concept of 'timedependent utilities' presented in Horvitz [10] to model decision problems where the utilities vary with the time taken to make the decision. According to this concept, timedependent actions can be represented by considering a continuum of decisions, each defined by initiating an action at a progressively later time, and by assessing the change in utility of the decision outcome as a function of time.

In formal terms, if H_i, D_j, t refers to an action D_j, taken at time t when state H_i is true, where t is defined in terms of an initial time t_o, the time when the decision problem begins, the utility of that action at different times t is given by $u(H_i,D_j,t)$. The losses with time can be modelled using, say, an exponential function as follows:

$$u(H_i,D_j,t) = u(H_i,D_j,t_0)e^{-\lambda t} - C_t \qquad (6)$$

where λ is a parameter constant, which we call the volatility of the product value with respect to time, and C_t is the cost of the tests conducted (for collecting information) till time t.

To understand the effect of information timeliness on product recovery decisions, we look at how the utility of making decisions evolve over a series of information gathering steps with time. Figure 8 provides a hypothesised picture of the dynamics involved in product recovery decision-making.

As described before, product recovery decisions are made after performing a series of tests on the product in order to collect more information associated with it. Figure 8(a) show how the certainty about the product state would increase as we conduct more tests on the product. However, increasing the number of tests translates to a decrease in benefits due to the increasing cost of conducting further tests as well the decrease in product value over time (refer to section 2.4). Since the expected utility of any product recovery decision is a function of the certainty about the product state and the benefit of making the decision at that point of time, the decision-maker will have to stop collecting information and make his decision at a point where any further benefits arising from increase in certainty is offset by the decrease in the benefit of making the decision as time passes (as represented the peak on the "utility" curve).

Now suppose the product has an RFID tag linked to networked information about its identity. This situation is represented in Figure 8(b) where an RFID enabled information system provides information that is normally obtained by conducting more than one test.

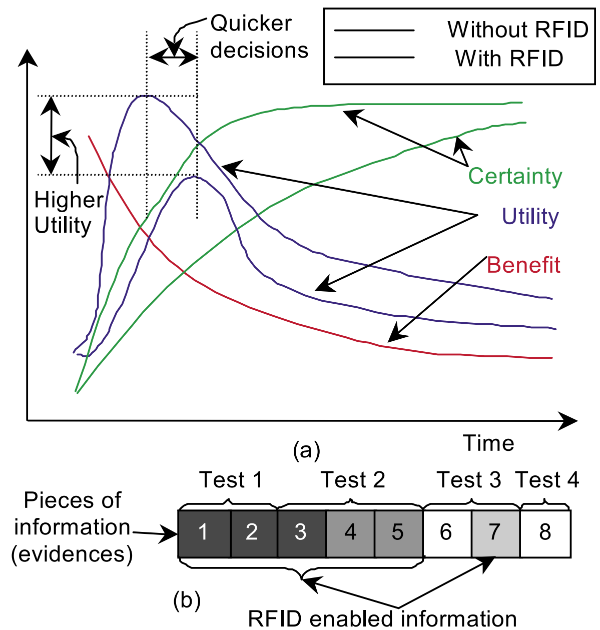

Fig. 8: The effect of information timeliness

The varying shades of grey tell us that while networked RFID can provide complete information about certain parameters, it would only be able to provide information that leads to increasing certainty about the values of other parameters. For e.g., suppose evidence 8 represents "wear" of a particular component. The networked RFID would potentially provide crucial lifecycle data such as usage rates and temperatures by attaching appropriate sensors to the tags, which would lead to a better estimation of the value of "wear".

This would lead to a higher rate at which certainty about the product increases (as shown by the dotted lines in Figure 8(a), which is skewed to the left), resulting in an expected utility curve that is more skewed to the left than that without such enhanced information. The outcome of this would be that the decision will be made much quicker, and the expected utility of the decision would be higher due to higher certainty and higher utilities.

5. Conclusions

There is a marked lack of timely information availability for making product recovery decisions which hampers the efficiency of product recovery operations. The low margins and increasing volatility of returned products make timely information gathering a high priority. From the observations made during this study, as well as from case studies conducted by other researchers, it is clear that this is an area with a lot of potential for bringing improvements to.

It was clear that the quality of product recovery decisions control the cost-effectiveness and viability of product recovery operations, and the quality of these decisions depend greatly on the quality of information made available to the decision-makers. Providing the ability to extract product information in a timely manner could bring two-fold benefits:

- *decision improvements* — being able to make informed decisions in a timely manner that could lead to higher profits, and
- *process improvements* — being able to facilitate automation of identification and sorting processes, thus improving the efficiency and costeffectiveness of product recovery operations.

Increasing the overall cost-effectiveness of operations could result in increased amounts of reuse of products and components in future.

It cannot be disputed that final testing of the product cannot be dispensed of even if the products are embedded with identification tags that enable ready identification. Nevertheless, the availability of lifecycle usage data would greatly improve the quality of decisions made as in many cases it would decrease the rigorousness of testing required to be performed. The concept of networked product identity would enable lifecycle usage data to be collected using appropriate sensors and to be linked directly to the product.

Although it can be seen on the outset that there are several benefits that can be brought about by such systems, it is important to realise that providing complete lifecycle information in a readily available format comes with a cost attached to it. In order to make a proper strategic decision about investment in product identification technologies, it is essential to quantify the impact of readily available product information on the effectiveness of product recovery decision-making and subsequently, the efficiency of product recovery operations as a whole.

AUTO-ID LABS

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