European Journal of Operational Research 198 (2009) 252–258

Contents lists available at ScienceDirect

European Journal of Operational Research

journal homepage: www.elsevier.com/locate/ejor

Decision Support

RFID and item-level information visibility

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ARTICLE INFO

Keywords:
RFID
Component manufacturing
Item-level information visibility
Decision making
Item-level identification

ABSTRACT

Radio frequency identification (RFID) is emerging as the hottest information tracing technology in supply chain management with its inherent ability to reveal item-level product information. Although the beneficial aspects for retailers have been studied in greater detail, RFID tags can be beneficially utilized in a manufacturing context. Unlike a majority of case study-based literature in this area, this paper takes a different perspective by modeling item-level information visibility in general. Specifically, this is accomplished through reduced randomness, as a function of the scale of the information system, the distribution of the sample space, the control variables and the production functions. In order to discover the optimal procedure that utilizes item-level information, we extend the basic model to cover multiple periods. Appropriate example scenarios are simulated accordingly to verify the results and to show evidence supporting the generality and robustness of the model.

1. Introduction

Radio frequency identification (RFID) is emerging as the hottest information tracing technology in supply chain management with its ability to reveal product information at an item-level in a way that is fully automatic, instantaneous, and touchless. RFID has been used in disparate applications to track and trace objects of interest. RFID tags can be used to store and retrieve relevant item-level product information (Raza et al., 1999; Shepard, 2005). Unlike competing technologies including bar codes that provide categorical-level information, RFID technology facilitates distinguishing individual product instances by assigning a unique electronic product code (EPC). Unlike bar codes, RFID tags do not require direct line-of-sight for data transmission, rendering it possible to simultaneously scan several tags as a batch.

It is becoming increasingly critical for companies to be knowledgable about an item's instantaneous status, the processes it has gone through, and its history of movements across transactions. An item's instantaneous status includes its unique identity, precise location, physical status, and other key features. An effective and efficient information tracking and tracing system enables a decision maker or an automated system to rapidly intervene in targeted situations to reduce operational cost and increase productivity (Piramuthu, 2005). Sahin et al. (2002) list potential benefits of RFID technology on supply chain processes including reduction in labor costs, increase in store selling area, acceleration of physical flows, reduction in profit losses, more efficient control of the supply chain through increased information accuracy, better knowledge of customer behavior, better knowledge of out-of-stock situations, reduction in delivery disputes, better management of perishable items, better management of returns, better tracking of quality problems, better management of product recalls and customer safety, and improved total quality control.

A majority of existing literature on RFID discuss the value of RFID through case studies (Dutta et al., 2007; Delen et al., 2007; Doeer et al., 2006; Karkkainen, 2007; Lee et al., 2005). Although case studies provide insights that are application specific, there is a paucity of analytical models (e.g., Gaukler et al., 2007) that are generalizable to a wide variety of applications. Our aim is to fill this gap by modeling the potential benefit of RFID in general using descriptive statistical analysis.

Several major retailers and manufacturers such as Wal-Mart and its suppliers have adopted RFID at the pallet level. However, estimating the direct benefits resulting from RFID adoption is not clear simply because of the general consensus that the last node downstream in the supply chain (e.g., Wal-Mart) benefits the most while the node at the other end of the supply chain (e.g., manufacturer) benefits the least from RFID technology. Given that this is a hotly debated issue, a purpose of this paper is to quantify the benefit of RFID adoption through reduction in uncertainty from a manufacturer's perspective. We describe the properties of this benefit function to provide managerial insights on whether, under what conditions, and the extent to which a firm should consider adopting RFID tag technology.

The primary thrust for RFID in supply chain management stems from its capability to provide item-level information visibility. Most of the potential benefits of RFID can be explained by reduced

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uncertainty as a direct result of item-level information visibility. This increased certainty improves supply chain coordination, reduces inventory, increases product availability, improves total quality, provides better management of perishable items and returns, among others. We use the factor of certainty as a key element to model the value of RFID information visibility.

The remainder of this paper is organized as follows: we provide a brief overview of extant literature in this area in the next section, followed by model setup in Section 3. Section 4 includes analysis and applications and Section 5 concludes the paper with a brief discussion.

2. Related literature

Although RFID tags have numerous advantages over bar codes (Raza et al., 1999; Shepard, 2005), its beneficial properties from a supply chain management perspective have not received much attention since its introduction during World War II. A majority of existing supply chain management literature involving RFID are case studies or simulations of domain-specific RFID implementations in inventory management and replenishment, supply chain operations, and retailing.

Atali et al. (2005) investigate the value of RFID under imperfect inventory information. Doeer et al. (2006) analyze the costs and benefits of RFID technology for the management of ordnance inventory using factorial structure for the non-cost related benefits of the implementation and traditional ROI analysis to assess the value of implementing RFID. DeHoratius et al. (in press) consider intelligent inventory management tools that account for recording errors using a Bayesian model, and also consider practical replenishment and inventory audit policies to illustrate how the needed parameters can be estimated using data from a large national retailer. Heese (2007) considers inventory record inaccuracy problem in a supply chain model by analyzing the impact of inventory record inaccuracy on optimal stocking decisions and profits. He finds that inventory record inaccuracy exacerbates the inefficiencies resulting from double marginalization in decentralized supply chains and that such a supply chain benefits more from RFID technology.

Gaukler et al. (2007) study item-level RFID in the Retail Supply Chain. Under the scenarios of dominant manufacturer or dominant retailer, they show how the cost of item-level RFID should be allocated among supply chain partners to optimize supply chain profit. Using a business case study of current leading practices for the adoption of Auto-ID system, Alexander et al. (2002) illustrate the impact of Auto-ID system on specific pain points faced by companies in the consumer goods and retail value chain. Fleisch and Tellkamp (2005) examine the relationship between inventory inaccuracy and performance in a retail supply chain and show that an elimination of inventory inaccuracy can reduce supply chain cost as well as out-of-stock level. Karkkainen (2007) discusses the potential in utilizing RFID technology for increasing efficiency in the supply chain of short shelf life products.

Lee and Ozer (2007) investigate the value of RFID in a supply chain. Dutta et al. (2007) examine three dimensions of the value proposition of RFID: generic architecture of RFID implementations and the drivers of value, measurement issues associated with quantification of value, and incentives for achieving diffusion when multiple independent organizations deploy the technology and coordinate the resulting information flows. McFarlane and Sheffi (2003) identify areas for short term deployment of Auto-IDl and highlight opportunities for longer term re-engineering of different sections of the supply chain.

Although most existing literature on RFID tags either mention or discuss them in the past, a comprehensive model of reduced uncertainty as a direct result of RFID item-level information visibility is missing in extant literature. From an extensive survey of literature in this area, the lack of mention of this specific advantage leads to the natural conclusion that this either has not been attempted at the industry level or the literature has not caught up with recent industrial trends.

3. Model setup

3.1. Motivating examples

RFID has the potential to greatly increase information visibility in a business supply chain at different stages including acquiring raw materials, manufacturing, transportation, and retailing. To illustrate how RFID visibility can possibly generate additional value to manufacturing, we consider the example of manufacturing a computer hard drive.

Quality and reliability have been major issues in computer hard drive manufacturing since its introduction because of its intrinsic design features consisting of high-speed motor and related moving components. The most common specification related to hard drive reliability is mean time between failure (MTBF). Schroeder and Gibson (2007) find evidence that failure rate does not remain constant with age. They also provide evidence of a significant early onset of wear-out degradation, which signifies inconsistencies in product quality. Elerath and Shah (2003) show that in hard drive manufacturing, there is a clear significant relationship between reliability and the number of mechanically moving read/write heads. They conclude that there is a critical need for design technology and manufacturing processes to advance fast enough to counteract potential degradation in reliability problems as faster drives are introduced.[1]

In summary, a major factor that influences hard drive quality and reliability is vibration that causes heat and noise, which are magnified to produce deleterious effects on reliability. A good yet simple solution is to measure and match components in order to reduce vibration and related attrition. However, this solution has not been attempted in the hard drive context because hard drive manufacturing generally involves large-scale mass production of several components. With its ability to record item-level information and to trace the location of individual items, RFID renders it possible for appropriate component matching even in a mass production scenario. Despite their ability to encode item-level information through complementary use of a related database, bar codes are not appropriate because of their lack of traceability that is necessary for automated mass production. In other words, in an automated manufacturing shop floor, it is extremely resource-intensive to simultaneously read every bar code to identify and locate the most appropriate instance of an item class. RFID tags, on the other hand, are a natural fit in this scenario and when implemented properly, they can be read simultaneously to improve productivity and overall quality. This is especially salient in automated environments where machines (e.g., robots) locate and pick the most appropriate part from a large number of similar parts for further processing.

Consider a simplified example of a hard drive which consists of two components: a spindle (A) and a casing (B). The manufacturer has two As and two Bs, all of which have passed quality checks based on tolerance levels, etc. The two spindles have the same part number except a slight item-level difference in tolerance. Similarly, the casing have minor differences in tolerance. We know that if A and B are connected too tight, the hard drive will have a short

[1] Research by the MMT Institute (MMT Institute, 1998) concludes that “part confusion is the number one cause of defects in manufacturing today. They also identify automated identification and pick-to-light as technologies to mitigate the problem.

MTBF because of low give and high heat. If A and B are connected too loosely, the hard drive will also have a short MTBF because of excessive vibration. Assume that the specifications for two spindles are $A_1 = 5$ millimeter and $A_2 = 5.1$ millimeter; the specifications of casings are $B_1 = 5.1$ millimeter and $B_2 = 5.2$ millimeter. Assume that we know MTBF from statistical analysis that $L(A_1, B_1) = L(A_2, B_2) = 4$ years, $L(A_1, B_2) = L(A_2, B_1) = 3$ years, where $\{A_1, B_2\}$ indicates a loose fit and $\{A_2, B_1\}$ indicates a tight fit.

Without RFID item-level information visibility and traceability, components are randomly chosen and assembled to form a hard drive that has an expected MTBF of $E[L] = E[E(A|B)] = 3.5$ years. With item-level visibility provided by RFID, the MTLB is $L = \max\{L(A_i, B_j),\ i, j \in \{0, 1\}\} = 4$ years. If we assemble two hard drives, the total life is 7 years without item-level information and 8 years with item-level information. This simplified example illustrates how RFID's item-level information visibility is able to generate additional value through optimal component matching. Mass manufacturing, in reality, may involve hundreds of components and millions of instances that complicate the process, but the basic principle remains the same as described in the example above. Moreover, RFID's remote traceability makes it possible for automated mass production with clear advantages over traditional bar code technology.

As another example, consider an electronics store that sells a new model of MP3 player. Assume that there is space for 20 units of this MP3 player on the self-service shelf. Every morning, before the store opens, the shelf is replenished to its full capacity of 20 units. We assume that the customers arrive according to a Poisson process with rate λ and each of them purchases an MP3 player with probability p. At any time in a day, the number of sold units (n) follows a Poisson distribution as

$$P(n) = \begin{cases} e^{-p\lambda t} \frac{p\lambda t^n}{n!} & \text{if } n19, \\ \sum_{n=20}^{\infty} e^{-p\lambda t} \frac{p\lambda t^n}{n!} & \text{if } n = 20. \end{cases}$$

We assume that the customers balk if the shelf is empty. Therefore, the expected sales per day is

$$S = \lambda p - \sum_{n=1}^{\infty} n \int_0^T e^{-p\lambda t} \frac{p^2 \lambda^2 (T-t)^n}{20! n!} dt,$$

units without RFID tagging, where $t \in (0, T)$ represents any time during the day when the store is open. With item-level RFID information visibility, the system is able to recognize when the number of items remaining on the shelf is low. This would soon be followed by necessary action to ensure that the shelf is never empty, and the expected sale would be the real demand (λp). In other words, the store could sell $= \sum_{n=1}^{\infty} n \int_0^T e^{-p\lambda t} \frac{p^2\lambda^2(T-t)^n}{20!n!} dt$ more units of the MP3 player per day as a result of incorporating RFID tags. In this example, if there are approximately 10 customers entering the store every hour during a 10-hour working day and if in general the consumer's willingness to buy this product is 20%, the expected sales without RFID information visibility is 18.76 units per day. The number of units sold with RFID is 20, and item-level information visibility results in 1.24 more sold units.

From the above examples, we observe that increasing item-level information visibility by deploying RFID generates more value compared to the same case without item-level information visibility. This theme recurs in almost all RFID case studies: without RFID, decisions are made based on categorical information; with RFID, decisions are made based on the decision makers' ability to find better strategies from revealed item-level information. In the next section, we illustrate this discussion by formulating a general model. We present a static model, and then extend this to incorporate a dynamic model scenario.

3.2. Static model

Consider a production scenario with m components $\{X|X_1, X_2, \ldots, X_m\}$ that join together to form a product. Each component X_i consists of n_i samples that share the same distribution such as $\{X_1|x_{11}, x_{12}, x_{13}, \ldots, x_{1n_1}\}, \{X_2|x_{21}, x_{22}, x_{23}, \ldots, x_{2n_2}\}, \ldots, \{X_m|x_{m1}, x_{m2}, x_{m3}, \ldots, x_{mn_m}\}$. Variables $X_1, X_2, \ldots, X_m$ follow joint distribution $f_{X_1, X_2, \ldots, X_m}(X_1, X_2, \ldots, X_m)$. The production function that maps components to a certain outcome is defined as $Y = g(X_1, X_2, \ldots, X_m,)$ with cdf (see Fig. 1):

$$F_y(y) = \int\int, \ldots, \int_{g(X_1, X_2, \ldots, X_m)y} f_{X_1, X_2, \ldots, X_m}(X_1, X_2, \ldots, X_m) dX_1 dX_2 \cdots dX_m. \tag{1}$$

Without item-level information visibility, a sample from each component is randomly chosen, with an expected production function value O defined as

$$O = E[y] = \int_y y dF_y(y). \tag{2}$$

With item-level information visibility, samples are selectively chosen in order to produce the maximum possible outcome $\widetilde{O}$, such that

$$\widetilde{O} = \max\{Y\}, \tag{3}$$

Y takes $N : \{N = n_1 \cdot n_2 \cdots n_m\}$ different possible values, so the distribution of $\widetilde{O}$ follows:

$$f_N^y(y) = Nf(y)F(y)^{N-1}. \tag{4}$$

The difference between the production functions with and without information visibility (δ) can therefore be written as

$$\delta = \int_y (Nu^{N-1} - 1) y u' dy, \tag{5}$$

where

$$u = F_y(y). \tag{6}$$

In reality, the production function usually involves more than just the best outcome. Under this situation, we are interested in the sum of the best k production and the distribution of the kth outcome can be described as

$$f_{k:N}^y(y) = \frac{N!}{(k-1)!(N-k)!} u^{k-1} (1-u)^{N-k} f_y(y). \tag{7}$$

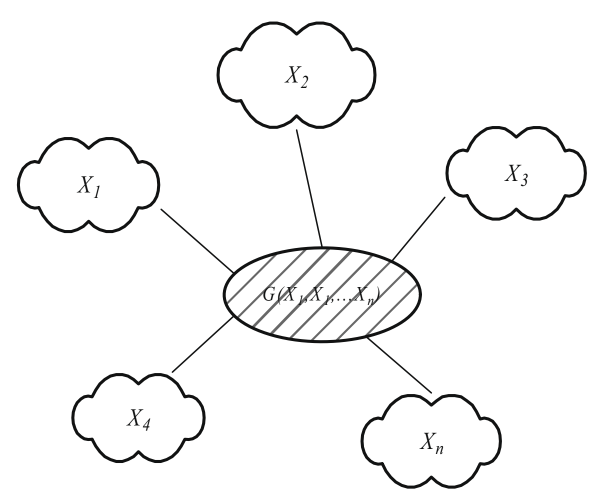

Fig. 1. m Components $\{X|X_1, X_2, \ldots, X_m\}$ that jointly form a final product.

The sum of the best k production therefore is

$$\sum_{i=1}^{k} E[y_{i:N}] = \sum_{i=1}^{k} \int_y y \cdot \frac{N!}{(i-1)!(N-i)!} u^{i-1}(1-u)^{N-i} f_y(y)\mathrm{d}y(8)$$

$$= \int_y nF_{binomial(N-1,u)}(k) \cdot yf_y(y)\mathrm{d}y.(9)$$

Hence the benefit of introducing RFID item-level information visibility is a function of the information scale (N), the distribution of the sample (F_x), and the production function ($G(\cdot)$), such that

$$\delta = (k, X, g(X)) = \sum_{i=1}^{k} (E[y_{i:n}] - E[y])(10)$$

$$= \int_y (NF_{binomial(N-1,u)}(k) - k) \cdot yf_y(y)\mathrm{d}y.(11)$$

Theorem 1. $\delta 0$.

Proof

$$\delta = \int_y yu'(nu^{n-1} - 1)\mathrm{d}y \int_y y\mathrm{d}u^n - \int_y y\mathrm{d}u$$

$$= yu^n|_y - \int_y u^n \mathrm{d}y - yu|_y + \int_y u\mathrm{d}y = \int_y (u - u^n)\mathrm{d}y$$

Because $u \in [0, 1]$, uu^n. Hence we show that δ is always greater than or equal to zero. Similarly, δ is greater than or equal to zero for the best k items. □

Theorem 2. *When kn,*

$$\delta \int_y (n\mathrm{e}^{-2\frac{(n-k)^2}{n}} - k) \cdot yf_y(y)\mathrm{d}y \int_y (n - k) \cdot yf_y(y)\mathrm{d}y.$$

Proof. The upper bound for the lower tail of the binomial distribution function can be derived using Hoeffding's inequality as

$F_{\mathrm{binomial}}(k; n, u)\mathrm{e}^{-2\frac{(n-k)^2}{n}}$.

The same results can also be derived using Chernoff's inequality. Since the cumulative function is less than or equal to one, there exists a loose upper bound given by

$F_{\mathrm{binomial}}(k; n, u)1$.

Therefore,

$$\delta = \int_y \left(n \sum_{j=0}^{k-1} \frac{(n-1)!}{j!(n-1-j)!} u^j (1-u)^{n-1-j} - k \right) \cdot yf_y(y)\mathrm{d}y$$

$$\int_y (n\mathrm{e}^{-2\frac{(n-k)^2}{n}} - k) \cdot yf_y(y)\mathrm{d}y$$

$$\int_y (n - k) \cdot yf_y(y)\mathrm{d}y$$

Theorem 3. *If* $k = n$, $\delta = 0$.

Theorem 3 can be easily shown to be true by replacing k with n in the original equation. Theorem 3 implies that if the experiment exhausts all the possibilities, the result with item-level information visibility and the one without item-level information visibility are not different.

Theorem 4. *The larger the sample space variance, the larger the benefit* δ.

Theorem 4 can be explained by the fact that with a larger sample space variance, there is a higher probability of observing large samples on the right tail. This also increases the density on the right tail for the order statistics, thus increasing the expected value.

Theorem 5. *if Y is positive,* δ *is a monotonic increasing function of n.*

Proof

$$\frac{\delta}{n} = \frac{\int_y yu'(nu^{n-1} - 1)\mathrm{d}y}{n}$$

$$= \int_y yu\prime(u^{n-1} + nu^{n-1} \ln(n-1))\mathrm{d}y0$$

Theorem 6. *If all the resources are used, the benefit of having item-level information visibility is zero if there is only one component; the benefit is greater than zero if there are multiple components.*

Proof. In the single case scenario, if all the n samples are used, the benefit of having item-level information visibility is

$$\int_y (nF_{\mathrm{binomial}(n-1,u)}(k) - k) \cdot yf_y(y)\mathrm{d}y.$$

It equals zero if $k = n$. In the scenario with multiple cases, this becomes

$$\int_y (NF_{\mathrm{binomial}(N-1,u)}(k) - k) \cdot yf_y(y)\mathrm{d}y,$$

where $N = n_1, n_2, \ldots, n_m$ and $k \in [0, \min\{n_1, n_2, \ldots, n_m\}]$. This is always greater than zero from Theorem 1. □

3.3. Multi-period dynamic model

3.3.1. Control function

Our discussion so far is based on the fact that sample X is static and non-changeable. Although this is valid in several circumstances, this may not be true once X is observed when the decision maker changes (improves) X in order to produce a better outcome. The second example of the electronic retailing store is such a case where X has only one sample that can be any number from 0 to 20. If x equals any number in $\{1, 2, \ldots, 20\}$, the decision maker takes no action. If x equals zero, the decision maker restocks, changing x back to 20. This process can be explained as adding a control function $\widetilde{X} = \psi(X)$ to the original sample, making the sample dynamic. In the previous example, $\widetilde{X}$ is given by

$$\psi(X) = \begin{cases} 20 & \text{if } X = 0, \\ X & \text{otherwise.} \end{cases}$$

The function $\psi(X)$ depends on the decision maker's business strategy and it may vary from case to case. We are interested in defining the optimal control function and its resulting production $Y = g(\psi(X))$. Overall, we conclude that the benefit of introducing RFID item-level information visibility is a function of the information scale, the distribution of the sample, the non-static function, and the production function,

$$\delta = (k, X, \psi(X), g(X)). \quad (12)$$

3.3.2. Finite time

In a multiple period scenario, the objective is to maximize the total production for the entire time period,

$$\max_{t} \{\delta(X_0, X_1, \ldots, X_T; {}_0, {}_1, \ldots, {}_{T-1})\}, \quad (13)$$

where ${}_t$ is a vector of control that can be chosen in every period by the decision maker, so that ${}_{t-1} = \psi_{t-1}(X_{t-1})$.

In a majority of scenarios in a business environment such as SCM, retail, or quality control, the production over a time period is the accumulated sum of utilities over separate time segments $\{t_0, t_1, \cdots, t_{T-1}, t_T\}$. Now we consider the case where the total production is time-separable. That is

$$\delta(X_0, X_1, \cdots, X_T; {}_0, {}_1, \cdots, {}_{T-1}) = \delta_0(X_0, {}_0) + \delta_1(X_1, {}_1) + \cdots + \delta_{T-1}(X_{T-1}, {}_{T-1}) + S(X_T),$$

where $S(X_T)$ is a "scrap value function at the end of the period where no further decisions are made. Let us define $\xi(\cdot)$ as an intertemporal function that connects the state and control variables such that $X_T = \xi_{T-1}(X_{T-1}, {}_{T-1})$.

Using Bellman's method, the recursive function is

$$V(X_{T-k}, k) = \max_{T-k} \{\delta_{T-k}(X_{T-k}, {}_{T-k}) + V(X_{T-k+1}, k-1)\} (14)$$

$$\equiv \delta_{T-k}(X_{T-k}, \psi_{T-k}(X_{T-k})) + V(\xi_{T-k}(X_{T-k}, \psi_{T-k}(X_{T-k}), k-1)),$$
(15)

subject to:

$1. X_{T-k+1} = \xi_{T-k}(X_{T-k}, {}_{T-k}, g({}_{T-k})), (16)$

$2. X_0 = \tilde{X}_0, (17)$

$3. {}_{T-k} = \psi_{T-k}(X_{T-k}), (18)$

$4. {}_t \in$ for all $t = 0, 1, \ldots, T-1. (19)$

In constraint 4, is the feasible set for the control variables that is assumed to be closed and bounded.

Because X_0 is given a value at the outset of the overall dynamic problem, we are able to solve for ${}_0$ as a number that is independent of the Xs. It is easy to compute X_1, and hence ${}_1$, from the control rule of that period, and then $X_2, {}_2$, etc. This process can be repeated until all the X_i and ${}_i$ values are known. Consequently, we are able to determine the optimal control function and its production outcome.

3.3.3. Infinite time

With non-deterministic control rules in a finite time context, we are able to find the optimization solution using a recursive algorithm. Now let us further assume that the control function is deterministic and has the same form in every period. By considering the future benefit in time value, we formulate the problem over infinite time as

$$V_t(X_t) = \max_{v_t} \{\beta\delta(X_t, v_t) + V_{t+1}(X_{t+1})\}, \quad (20)$$

subject to:

$1. X_{t+1} = \xi_0(X_t, v_t), (21)$

$2. X_0 = \tilde{X}_0, (22)$

$3. v_t = \psi(X_t), (23)$

where β is the discount factor and $0 \beta 1$. By defining

$$W_t(X_t) = \frac{V_t(X_t)}{\beta}, \quad (24)$$

we can write Eq. (20) in current value as

$$W_t(X_t) = \max_{v_t} \{\delta(X_t, v_t) + \beta W_{t+1}(X_{t+1})\}. \quad (25)$$

The above iterations starting from any bounded continuous W_0 will cause W to converge as the number of iterations becomes large (Sargent, 1987; Stokey et al., 1989). Moreover, the $W(\cdot)$ that comes out of this procedure is the unique optimal value for the infinite horizon maximization problem. Since $W(\cdot)$ is uniquely associated with the control function $\psi(\cdot)$, we can determine the maximum production over time once we know the optimal control rule.

4. Analysis and applications

In this section we test the model proposed earlier by simulating a simplified business scenario of manufacturing quality control. We simulate a cost benefit analysis application of adopting RFID technology by assuming a linear cost function. Furthermore, we extend the existing model to investigate the scenario with incomplete information.

4.1. Simulation of fabrication quality control

In the first example, we investigate a quality control scenario using RFID item-level information visibility in a bottle manufacturing plant. Let us assume that the manufacturer makes plastic bottles by fitting a cap to a body. The size of the cap and the size of the body follow certain known distributions respectively. Because all caps (or the bodies) are manufactured in the same line, we assume that every instance of bottle cap follows the same distribution $f(X_1)$. We also assume that every instance of bottle body follows $f(X_2)$. The quality of the final product is defined as an exponential function of the difference in size (tolerance or fit) between the cap and the body $G(X_1, X_2) = e^{x_1 - x_2}$. Assuming that there is no further processing on either of the components, $\psi(X) = X$.

The simulation result shows (Fig. 2) that the benefit of item-level information visibility increases with the manufacturing scale (Theorem 6). The benefit function is concave and bounded (Theorem 2). We experiment with four different sample spaces with different volatile levels (variance) and find that if the samples are more volatile, the more is the benefit of having RFID item-level information visibility (Theorem 4). This can also be explained by the observation that when the sample spaces have large variance, there is more randomness. RFID as a means to reduce randomness benefits more as a consequence.

4.2. Cost benefit analysis

We illustrate a simplified managerial policy problem in a manufacturing setting using this model. We define the scalability of the item-level information system $n = n_1 + n_2 + \cdots + n_m$ as the number of RFID tags attached to m different parts that are mass manufactured. Marginal cost per RFID tag includes tag unit cost and incremental maintenance cost. We therefore have a linear cost function $c(n) = a\sum_{i=1}^{n} n_i + b$, where b denotes the sunk cost and a denotes the marginal cost. The overall profit in adopting RFID tags is

$$= \delta(n) - c(n) (26)$$

$$= \int_y y u'(n u^{n-1} - 1) \mathrm{d}y - cn - b. (27)$$

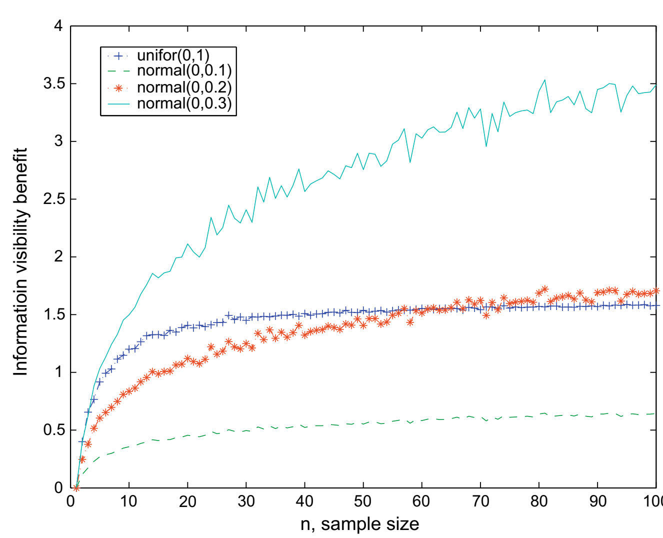

Fig. 2. Benefit of item-level information visibility for fabrication quality control.

By taking the first order derivative on n, $/n$, we can find the optimal scale of the information system that would bring the maximum benefit through item-level information visibility,

$$\frac{}{n} = \int_y yu'(u^{n-1} + nu^{n-1}\, ln(n-1))\mathrm{d}y - c$$
$$= \left(\frac{1}{n} + ln(n-1)\right) \cdot \int_y ynuu^{n-1}\mathrm{d}y - c$$
$$= \left(\frac{1}{n} + ln(n-1)\right) E[y_n] - c$$
$$= 0.$$

By solving the first order condition problem, we are able to determine the optimal scale of the information system that is dependent on the marginal cost of RFID technology, the distribution of the samples, and the production function.

4.3. Incomplete information

Although several leading retailers and their vendors have begun to adopt RFID technology, many others are still hesitant to do so mostly because the potential benefits and possible problems associated with implementing RFID traceability technology are not clear from both industrial and academic research perspectives. As a consequence, the business world will see a mixture of the non-visible traditional supply chain and the RFID enabled item-level information visible supply chain in the near term. It is natural to assume that the RFID enabled item-level information visibility is not always complete and therefore there is a need to consider such a problem of optimization when incomplete information is present.

Here we describe the incomplete information problem when not every component in the business chain is information traceable. The information incompleteness may be caused by the fact that not all upper-stream partners are equipped with necessary RFID infrastructure so that only a portion of the products acquired have item-level information visibility (Fig. 3). Information incompleteness may also be caused by the fact that some of the components don't have information visibility horizontally in the system (Fig. 4). Information incompleteness arises both at vertical and horizontal levels. When information is not complete, it is natural for business practitioners to be interested in knowing the optimal percentage of information coverage, the minimal required coverage, upstream and downstream relationship and the strategies for partial tagging. Using the results derived from Section 3, we find the absolute value of partial information in a horizontal one component example as

$$\delta(\tilde{n}, k, X, g(X)) = \int_y (\tilde{n}F_{\mathrm{binomial}(\tilde{n}-1,u)}(k) - k) \cdot yf_y(y)\mathrm{d}y, \tag{28}$$

where $\tilde{n}$ denotes the magnitude of available information. Recall that n is the magnitude of original information, including both visible and invisible components. Then $n - \tilde{n}$ is the magnitude of the invisible information. By assuming that the order statistics of the sample is symmetric we find that the value of information visibility comes from the first half of $\tilde{n}$. It implies the overall benefit of having item-

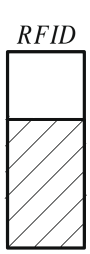

Fig. 3. Vertical incomplete information.

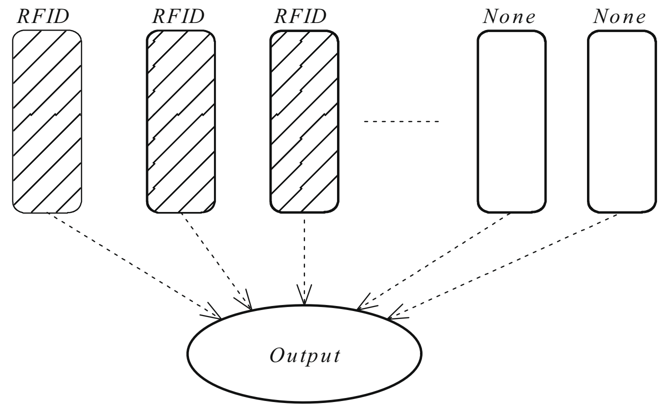

Fig. 4. Horizontal incomplete information.

level information visibility is the same as Eq. (28) if $k\frac{\tilde{n}}{2}$. Otherwise it becomes

$$\delta = \int_y \left(\tilde{n}F_{\mathrm{binomial}(\tilde{n}-1,u)}\left(\frac{\tilde{n}}{2}\right) - \frac{\tilde{n}}{2}\right) \cdot yf_y(y)\mathrm{d}y. \tag{29}$$

The derivation of horizontal incomplete information and the mixed incomplete information involves Bayesian conditions and a new model. This is left as an exercise for an extension of this paper.

5. Concluding remarks

Radio frequency identification is currently one of technology's hot focus area, enabling information traceability beyond the physical supply chain processes of manufacturing, distribution and retail. While RFID is viewed eagerly by some as a replacement for bar codes, the potential benefits of RFID is not clear to both business practitioners and academic researchers. To fill the gap in academic research literature as well as to provide insights for RFID business adopters, we have attempted to quantify the benefit of RFID item-level information visibility by considering the benefit as reduced uncertainty in both static and dynamic scenarios.

We show that the benefit of RFID item-level information visibility as a result of reduced randomness is a function of the scale of the information system, the distribution of the sample space(s), the revenue functions and the control function. Our analysis shows that the benefit due to item-level visibility increases with the scale of the information system and is bounded. The results also show that visibility has no value if all the samples are used in the case of a simple component and that it's greater than *zero* in case of multiple components. Our result also provides a basis for studying decision makers' optimal control when information in multiple periods are known.

Of course, the analysis presented here leaves many interesting questions in the field of RFID item-level visibility unanswered. One important aspect of the problem, which we have not considered, is that RFID read rate is not always 100% accurate and under certain circumstances the reading accuracy can be very poor (Tu and Piramuthu, 2008a,b). While assuming false reads as correct and using them for decision making, we naturally come to the interesting problem on the extent to which we should incorporate RFID and the need for a new business strategy if we know that the read rate accuracy is not always 100%.

As an extension to this paper, we are working on a related interesting problem due to incomplete information coverage that is also a current problem facing the industry and will remain for many years to come. A preliminary observation with respect to this problem is that the incomplete portion of the information can be within a single component or across different components in a business supply chain and that there should exist an optimal business strategy in situations with partial information coverage.

Acknowledgements

The author would like to thank the two anonymous reviewers for thoroughly reading the paper and for their help in improving the presentation of this paper.

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