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An Integrated Planning System for Managing the Refurbishment of Thermoluminescent Badges

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ABC Worldwide Dosimetry Service provides a high-quality service for measuring and reporting radioactive exposure at its customers' sites. It leases thermoluminescent badges that record radioactive exposure over a prespecified time period. As each recording cycle ends, ABC must send refurbished (or new) badges to the customers before they return the old badges to ensure continuous monitoring. It then measures, recalibrates, and refurbishes the returned badges for future use. We developed an integrated system that could help ABC to manage its purchasing schedule for new badges so it can meet a target customer service level with minimal inventory. We ran our integrated system using the data ABC provided and found that our system could have helped ABC to reduce its inventory level by 17.7 percent and its costs by $820,000 within a six-month period.

Key words: inventory: production, applications; industries: pharmaceuticals.
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United States federal law requires high-risk facilities, such as X-ray laboratories and nuclear plants, to monitor employees continuously and report radioactive exposure periodically. Many firms outsource the monitoring and reporting services to ABC Worldwide Dosimetry Service, a company that provides accurate, low-cost services for recording, measuring, and reporting radioactive exposures. (We are disguising the name of the company to protect company confidentiality and using ABC as a generic company name.) ABC is one of the world's largest providers of radiation dosimetry services. It provides various types of reusable (or recoverable) thermoluminescent badges that record the cumulative radioactive exposure of workers over a prespecified period of time.

ABC leases 20 types of thermoluminescent badges. They differ in the underlying recording and measuring technologies for different types of radiation. For example, one type monitors high neutron energies while another monitors only X-rays. Depending on these needs and the federal law requirements for different industries, customers lease different types of badges. Among those 20 types of badges, badge types 14, 16, and 19 account for over 75 percent of the total demand at ABC. We focus on these three types; however, our system and analysis can be used to manage all types of badges.

Because the federal requirements differ for different industries, each customer contracts with ABC to record and measure the amount of radioactive exposure over a prespecified recording cycle throughout the lease period. The recording cycles usually last a month, a quarter, or six months, depending on the customer's industry characteristics or operation policy. Customers who demand the same badge type with the same recording cycle are usually in similar industries and have similar return characteristics. To simplify the analysis, we aggregated all customers with the same recording cycle into a single customer group for each badge type. For example, we aggregated all customers who lease badge type 16 with a quarterly recording cycle into one customer group.

At the beginning of each recording cycle, ABC assembles employee-specific wearable badges (Figure 1). It calibrates each refurbished or new raw badge by setting the radiation counter to zero, it imprints the name of the company and the name of the employee on a separate plastic plate, it joins the name plate and the raw badge, and it laminates the unit with a plastic clip so that the employee can wear the customized badge as an identification card throughout the recording cycle.

At the end of each recording cycle, ABC must ship the replenishment badges to customers before they return the old badges. The facilities monitor their employees' radioactive exposure continuously. The managers distribute the customized badges and simultaneously collect the old badges from their employees. When ABC does not have enough raw badges available, it back-orders the demand and notifies its customers to have their employees continue to wear the old badges beyond the specified recording cycle. ABC then waits for its supplier to deliver

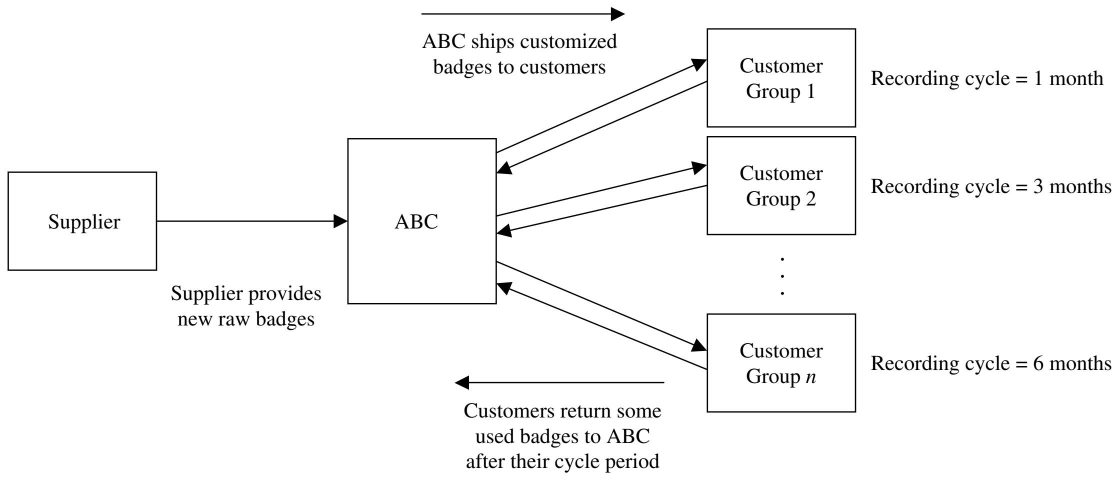

Figure 1: ABC sends refurbished badges to its customers at the beginning of each recording cycle. The customers return used badges to ABC at the ends of their recording cycles, but the returns are not in full amount. ABC purchases new badges from its supplier to replenish its badge inventory.

new raw badges or for customers to return old badges. It cannot expect to get returns until it supplies replenishments.

After it ships customized badges to its customers, ABC asks them to return the old badges so that it can measure the amount of radioactive exposure recorded on each badge. Depending on the efficiency of the customer's managers, the customers may take up to two months to return the old badges after they receive new badges. Customers also lose or damage badges, causing a loss of around 10 to 15 percent of the badges.

To process the returned badges, ABC first removes the plastic clip, the lamination, and the nameplate from each badge to retrieve the recordable element. It then measures the amount of recorded radioactive exposure and generates a report for each employee. If it notices irregular measures of radioactive exposure recorded on the old badges, it notifies customers immediately so that they can take the necessary safety measures. ABC then determines whether it can refurbish the old recordable badges and reuse them as raw badges. It scraps any damaged badges. ABC either scraps old badges or refurbishes and reuses them. In some other situations, firms scrap, recycle, or refurbish and reuse returned products. Rudi et al. (2000) developed a model to help the Norwegian National Insurance Administration decide when to scrap and recycle wheelchair parts and when to refurbish and reuse the wheelchairs the Norwegian government provided.

As ABC expands, it encounters three types of uncertainties: (1) because of staff changes at the customers' sites, the demand for customized badges fluctuates from cycle to cycle; (2) because managers' efficiency varies, the return time for old badges is uncertain; and (3) because of mishandling and wear, the yield of reusable old badges from those customers' returns is uncertain. When delivering customized badges to its customers worldwide, ABC finds it difficult to match the uncertain demand for customized badges with the uncertain supply of reusable raw badges.

To supplement any potential shortfall of reusable badges, decision makers at ABC purchased too many new raw badges from the suppliers too frequently, basing their decisions mainly on intuition. ABC managers therefore sought to develop an effective new-badge-purchasing system to achieve four major objectives:

(1) To maintain a target customer-service fill rate, defining the fill rate as the percentage of demand satisfied from the inventory of (refurbished or new) raw badges,

(2) To minimize the average inventory level of raw badges,

(3) To minimize the total costs associated with raw badges, which include a fixed ordering cost, a purchasing cost per unit, and an inventory holding cost, and

(4) To respect the supplier's capacity constraint for orders of new raw badges.

To develop a system to achieve these objectives, ABC formed a team comprising Kip Bennett, Luis Espada, Sander Perle, and Joel White of ABC, and Murat Bayiz and Christopher Tang of UCLA. The team developed a model that examines the following questions:

(1) Is it possible to develop a model to forecast the demand from customers at the beginning of each

recording cycle and the number of old badges customers will return after each recording cycle?

(2) In view of the uncertain return of old badges, how should ABC determine the target inventory level of raw badges to provide good customer service?

(3) To meet uncertain future demand for customized badges, ABC may need to order some new raw badges to supplement potential shortfalls in returned badges. What is the most cost-efficient purchasing schedule for new badges?

(4) To reduce its inventory of raw badges, ABC may develop incentives for customers to return the old badges promptly. What is the cost-benefit to ABC of customers returning the old badges promptly?

(5) To reduce the number of badge types, ABC might develop a badge type that would substitute for multiple types. How would it affect operating cost?

To our knowledge, no existing inventory-planning system deals with uncertain supply in terms of return and uncertain demand for customized badges. This is because ABC's situation differs from those described in the literature. For instance, Toktay et al. (2000) developed an inventory-planning system for managing new-components inventory for a remanufacturable product (such as Kodak's single-use camera). Toktay et al. assumed that the return cycle was exponentially distributed, while ABC's intended return cycle for each customer is dictated by a specified recording cycle time. However, customers may return the used badges late.

Developing an inventory-control system to achieve all four objectives simultaneously is too difficult. We developed an integrated inventory system that allows us to achieve the four objectives sequentially. Before implementing our system at ABC, we tested it over a six-month period using historical data. The results showed that if our system had been used over the past six months, it would have reduced ABC's average inventory by 17.7 percent and its costs by $820,000. Because our integrated system captures the essence of inventory management of recyclable products, we believe our system can be adapted to handle other situations that deal with refurbished products.

Integrated Planning System

Our planning system consists of three modules; a forecasting module, a planned-ordering module, and an optimal-ordering module. In the forecasting module, we used a seasonal decomposition approach to develop a forecasting model based on historical demand and return data. In the planned-ordering module, we used forecasted demand and forecasted return to plan purchases for new badges and target inventories for each badge type to meet specified service levels. This module would enable ABC to minimize its inventories of raw badges while meeting its target service level. In the optimal-ordering module, we used the information about planned purchases for new badges, fixed ordering and inventory costs, and the supplier's production capacity for new badges to determine an optimal ordering schedule for new badges. This module would enable ABC to minimize the costs associated with raw badges while respecting the constraint of supplier's capacity.

The Forecasting Module

The forecasting module forecasts demand for customized badges and the return of old badges over time. First, we used historical data to predict future demand for badge types 14, 16, and 19, which account for over 75 percent of ABC's total demand. We classified customers into three groups corresponding to their recording cycles of one, three, or six months. The total demand for badge type 16 from the three customer groups has a seasonal cycle of six months (Figure 2). A six-month cycle has two peaks, one due to the quarterly customer group and the second due to the quarterly plus the biannual customer groups. Similar seasonal patterns prevail for types 14 and 19.

We used the historical data to create demand forecasts for the three customer groups. By adding the three forecasts, we obtained a total demand forecast. Our forecasting module uses seasonal decomposition to capture the seasonality effect (Nahmias 2001, pp. 81–83). We tested our forecasting algorithm using the actual demand data for the period between February 2001 and December 2002. We first used actual demand data for February 2001 to July 2002 to

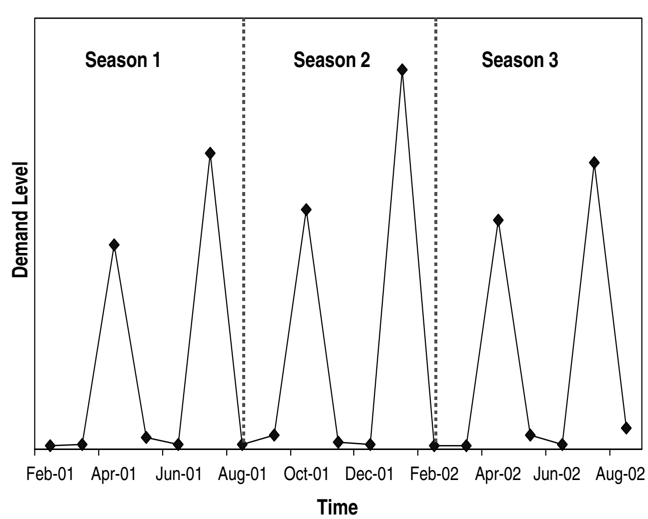

Figure 2: Total demand for badge type 16 has a seasonal pattern with a cycle of six months. We have disguised actual demand volumes to protect company confidentiality.

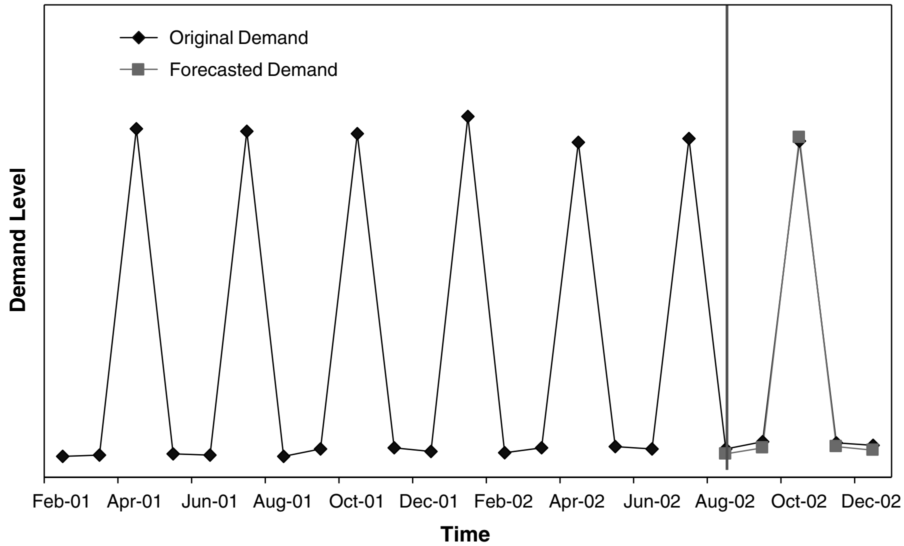

Figure 3: The forecasting module produces accurate forecasts for badge type 14.

calibrate and estimate the seasonality factors. Then, we produced demand forecasts and compared them with actual demand for August 2002 to December 2002. The module captured the underlying seasonal pattern and provided very accurate forecasts (within five to seven percent) for all three types (Figures 3, 4, and 5).

ABC collected information only about the number of badges customers returned. Because it did not collect information about the exact timing of the returns, we did not have time-series data for the returns. Hence, we could not use the same approach we used to forecast demand to forecast returns. Instead, we developed a model for predicting returns based on the actual demand information. ABC collected some return data for February 2002 to July 2002 for badges 14, 16, and 19. This data showed that customers return a certain percent of used badges within one month after the recording cycle and return almost all of the badges within two months. We modeled these return rates as random variables and used the historical data to estimate the mean and the standard deviation of the return rate within the first month and the return rate within the second month.

To simplify the exposition of our return forecasting method, we will consider the case of one customer group with a recording cycle of one month. In this case, the number of badges to be returned in month t

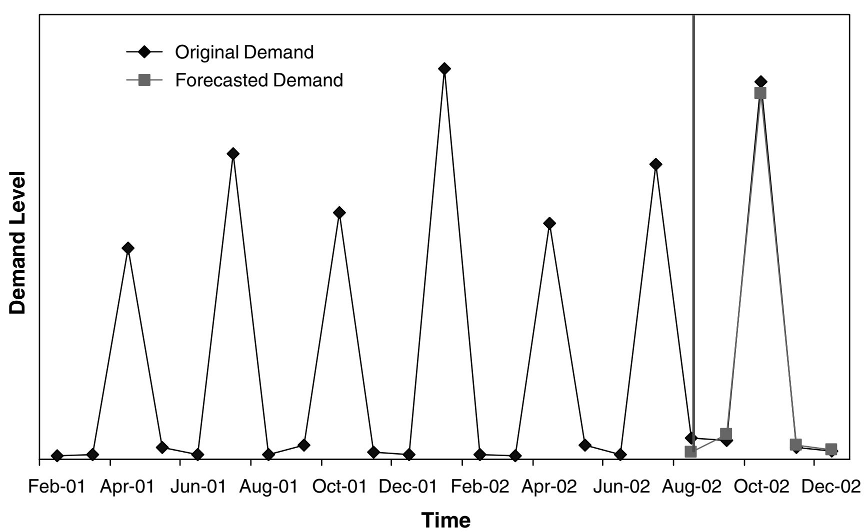

Figure 4: The forecasting module produces accurate forecasts for badge type 16.

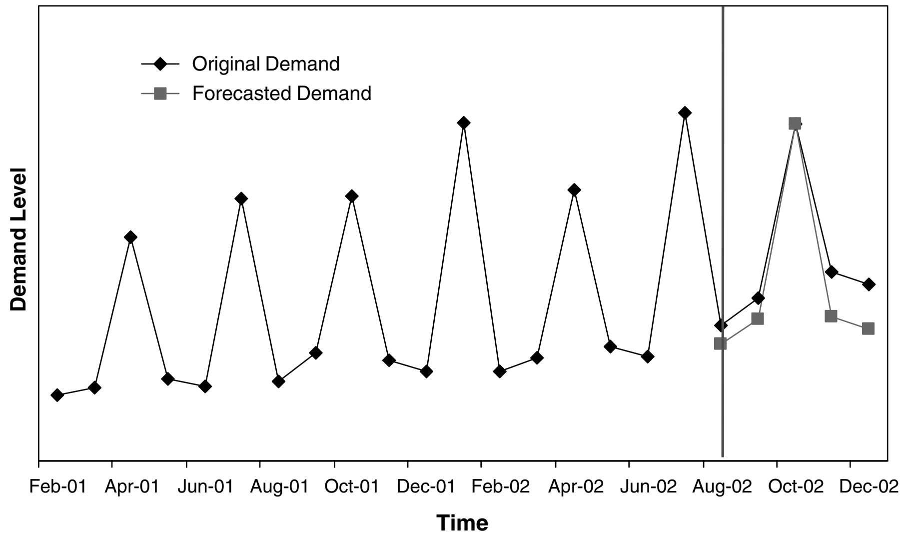

Figure 5: The forecasting module produces accurate forecasts for badge type 19.

is governed by the following equation:

$$\begin{aligned}&\text{number of badges returned in month } t\\&\quad= \text{first month return rate}\\&\qquad * \text{demand for badges in month } (t-1)\\&\qquad + \text{second month return rate}\\&\qquad * \text{demand for badges in month } (t-2).\end{aligned}$$

The analysis for multiple customer groups follows a similar formulation (appendix).

To forecast the number of badges to be returned in the future, we first forecasted the demand and estimated the mean and standard deviation of the return rates using historical data. Then, we substituted the resulting information into the above equation to estimate the mean and standard deviation of the number of badges to be returned in the near future. To validate this approach, we first used the demand data for February 2001 to January 2002 to calibrate the seasonality factors for the demand forecast. We then forecasted demand and used the equations in the appendix to estimate the number of badges returned during the validation period of February 2002 to July 2002 for each customer group. Finally, we compared the actual data ABC collected and the forecasted returns during this validation period and found that the average forecast error was 24 percent.

To obtain a tractable solution in the planned-ordering module, we assumed that the underlying demand for customized badges in each time period is normally distributed. To validate this assumption, we conducted the Kolmogorov-Smirnov goodness-of-fit test to check whether the actual monthly demand for customized badges of each type is normally distributed (Banks 2001).

Our empirical test showed that we could not reject our assumption that the underlying demand is normally distributed. Even with normally distributed demand, we could not determine the distribution for the number of badges to be returned in each month (as stated in the equation above) analytically, because the return rates are random variables as well. However, we again applied the Kolmogorov-Smirnov goodness-of-fit test to the historical return data, and the test results showed that we could not reject the assumption that the number of badges to be returned in each month is normally distributed.

Planned Ordering Module

For two key reasons ABC must order new raw badges from time to time: because some customized badges are lost or damaged, and because the return rates of the old badges are uncertain. We developed the planned-ordering module to determine the minimum quantity of new badges ABC should order over the planning horizon to meet its target customer-service level. We defined the service level in terms of fill-rate; that is the percentage of demand that ABC can handle by using its on-hand inventory of new and refurbished raw badges. To develop a practical approach, we did not consider the supplier's capacity, the fixed ordering cost, and the inventory holding cost in this module. We considered these issues in the optimal-ordering module. In the planned-ordering module, we took the following factors into consideration:

(1) The supplier's replenishment lead time for new badges (the time between the order and delivery);

(2) The distribution of the total demand for customized badges over the replenishment lead time;

(3) The distribution of the total number of old badges returned to ABC over the replenishment lead time;

(4) The on-hand and on-order inventory levels of raw badges over the replenishment lead-time; and

(5) The net requirement for raw badges over the replenishment lead time, which is essentially the difference between the total demand for customized badges and the total number of old badges to be returned over the replenishment lead time.

Because the demand and returns in each month are normally distributed, the net requirement for raw badges over the replenishment lead time is also normally distributed. By viewing the net requirement for raw badges as the effective demand and by considering the inventory position of the raw badges, we can use the well-known order-up-to policy to determine the minimum order quantity for new badges over the planning horizon needed to meet ABC's target customer-service level (Nahmias 2001, pp. 259–262).

Optimal Ordering Module

The minimum order quantity generated by the planned-ordering module may not be cost effective, and it may not be feasible because the module does not take into consideration the relevant costs (fixed ordering cost, variable cost, and inventory-holding cost) and the supplier capacity. In the optimal-ordering module, we treated the minimum order quantity determined by the planned-ordering module as the desired shipment in each period. Given these desired shipments, we formulated a mixed-integer program to determine the optimal order quantity in each period. The objective function of this program captures the total fixed ordering cost, the variable cost, and the inventory-holding cost associated with the new raw badges. The constraints include the supplier capacity constraint and the inventory balance equations (appendix).

Decision-Support System and Implementation Results

We developed a decision-support system to help ABC managers understand the actual demand and the future demand forecasts, the actual returns and the future return forecasts, and the planned-order quantity and the optimal-order quantity in each month. ABC asked us to develop a system with the following characteristics:

—The system should be simple, intuitive, and easy to use.

—Data entry should be simple.

—The output of each module should be displayed in graphical form.

—The system should be simple to maintain and to modify.

—The system should allow users to perform what-if analyses.

To develop a system that integrates all three modules, executes them automatically, and meets ABC's requirements, we developed a Visual-Basic-based application. The application includes the automatic execution of Excel Solver for solving the mixed-integer program in the optimal-ordering module. To make the system user friendly, we also developed a graphical user interface (GUI) that allowed us to customize the input and output interfaces for ABC managers. We developed the decision-support system in December 2002, and ABC managers have been using it since January 2003.

Kip Bennett of ABC uses this integrated system to forecast demand, to monitor returns of the old badges, to monitor the inventory of raw badges, and to determine the order quantities for new raw badges. The system can be used for other purposes. For example, the demand forecast can be helpful to those developing sales, budget, and strategic plans, and the planned order quantity can be valuable to those negotiating supply contracts.

Even though ABC has been using the system successfully, because of business transitions, we could not isolate and quantify the benefits of the system. Therefore, to demonstrate the usefulness of the integrated system, we compared system results with the actual events at ABC. We used historical data from February 2001 to January 2002 to calibrate our forecasting module. Then, we compared historical data on the actual events from February 2002 to July 2002 with the results obtained by our integrated system during the same time period.

ABC managers set the target customer-service fill rate at 85 percent. We used the same service level in our calculations. We executed our system in a rolling-horizon manner. For example, at the beginning of February 2002, we forecasted demand and returns for the following six months and determined the forecasted net demand for each of the three badge types. We used these forecasts to determine the planned order quantities and the optimal order quantities for the next six months. Then, at the beginning of March 2002, we repeated the same steps based on updated demand and return information. Using this process, we determined the optimum purchase quantities and the corresponding inventory levels. We then compared ABC's total actual inventory level from February 2002 to July 2002 with the inventory levels our system generated for badge types 14, 16, and 19. Had ABC ordered the new badges using our system, it could have reduced its total inventory level for the three badge types by 17.7 percent (Figure 6).

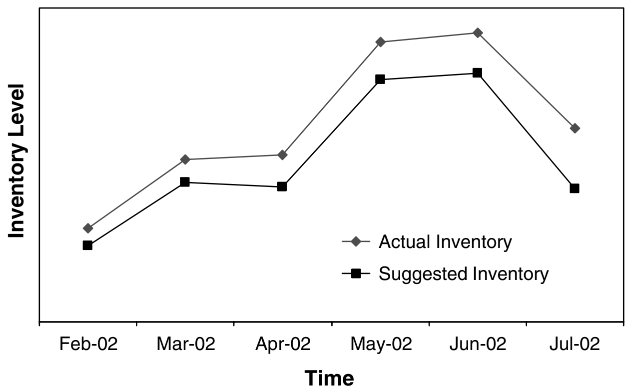

Figure 6: The decision-support system reduced the total inventory levels for the three badge types by 17.7 percent over the six months validation period.

As for the inventories for individual badge types, our system could have helped ABC to reduce its inventory levels for all types had it used the system during the validation period (Figures 7, 8, and 9). The inventory reduction for badge type 14 was smaller than it was for the other two badge types. Our system did not achieve as great a reduction of inventory for badge type 14 as it did for 16 and 19, because ABC reduced the quantity of badge type 14 it ordered in anticipation of its obsolescence. ABC plans to develop a new badge type that will substitute for badge types 14 and 16. This new badge type is essentially badge type 16 with a newly designed integrated circuit (IC) chip. Therefore, ABC did not need to reduce the order quantity for badge type 16.

Our system could help ABC to reduce inventory

(1) By providing it with a systematic way to forecast demand and returns,

(2) By using a scientific approach to plan order quantities of new badges, and

(3) By using an optimization model to determine order quantities for new badges.

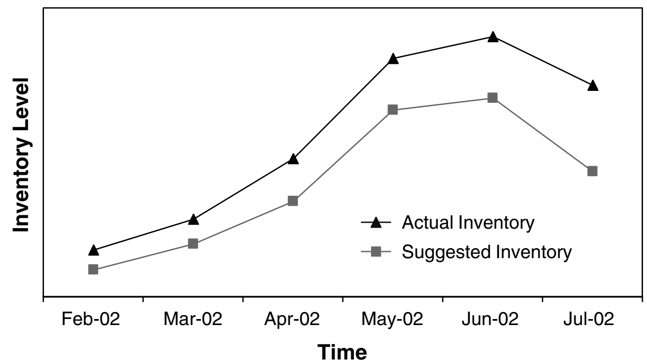

Figure 8: The decision-support system reduced the total inventory levels for badge 16.

ABC can now order the right number of badges at the right time to avoid unnecessary orders for new raw badges. Had the firm used our system to plan its orders, it could have reduced the quantity of new badges it ordered by 84 percent, which corresponds to about \$750,000 in savings during our six-month validation period. With fewer orders, ABC could have reduced its inventories by 17.7 percent, which corresponds to about \$70,000 in savings in holding costs during our validation period. Therefore, had ABC used our system to order badges during the six-month validation period, it could have saved \$820,000.

Other Managerial Considerations: Prompt Return of Old Badges and Development of New Product

ABC is developing incentives to entice customers to return the used badges promptly, say, within one month after the recording cycle. Because timely returns would reduce the variance in the number of returned badges, this would also reduce the variance

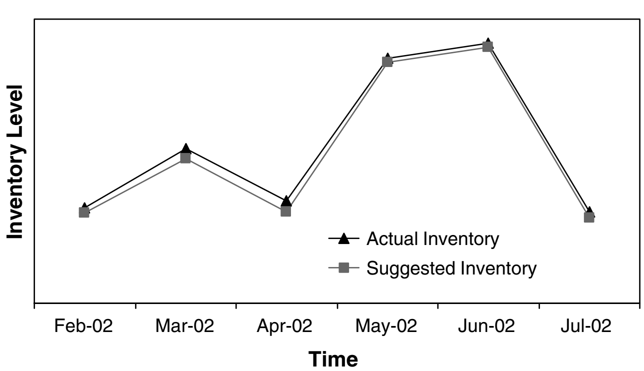

Figure 7: The decision-support system reduced the total inventory levels for badge 14, but because of its anticipated obsolescence, the improvement was not substantial.

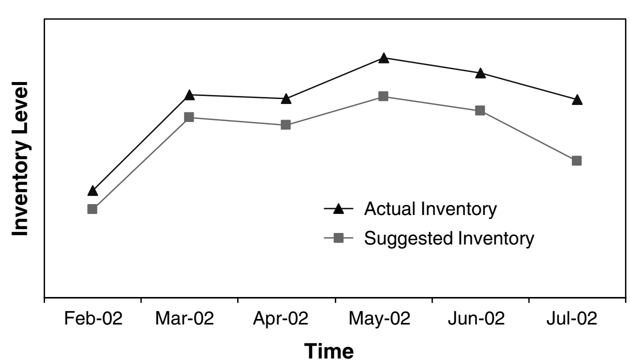

Figure 9: The decision-support system reduced the total inventory levels for badge 19.

in the net requirement for raw badges, allowing ABC to lower the order-up-to inventory level and the quantity of new raw badges it orders. In determining the incentives, ABC can use our system to evaluate the savings it would realize if customers returned the used badges promptly. When customers return badges promptly, the effective return rate within the first month will be equal to the sum of the return rates within the first and second months. The effective return rate within the second month will be equal to zero. We ran our system again considering the effective return rates. In addition, we compared the inventory level for this case, the actual inventory level, and the inventory level for the original case had ABC used our system (Figure 10). Timely returns of old badges would enable ABC to reduce inventory levels for all three major badge types by 21.3 percent. Our system would reduce the inventory level of new raw badges by 17.7 percent (Figure 4). Therefore, prompt returns could reduce inventories by an additional 3.6 percent. With prompt returns, ABC could reduce the quantities of new badges it ordered by 96 percent. By ordering fewer new badges and holding fewer inventories over the six-month validation period, ABC would have saved $120,000.

We used our system to evaluate the impact of ABC's modifying badge type 16 to serve as both the current badge type 16 and badge type 14. Pooling demand for badge types 14 and 16 reduces the variance in net demand and therefore reduces inventory. We ran our system for this scenario and found the total inventory level would be 19.3 percent lower than the actual inventory level (Figure 11). Because our system would reduce the inventory level of badges by 17.7 percent, modifying badge type 16 could further reduce inventory by 1.6 percent. Using our system and modifying badge type 16 would also cut order quantities of new badges by 95 percent. By ordering fewer new badges and holding lower inventories over the six-month validation period, ABC would have saved $110,000.

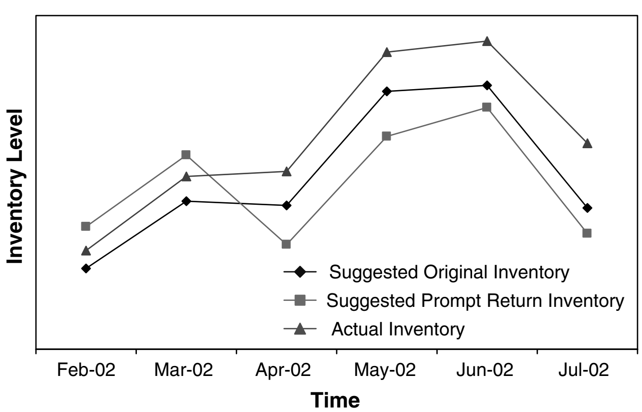

Figure 10: Using our decision-support system and giving incentives for prompt returns would help ABC to reduce its total inventories by 21.3 percent.

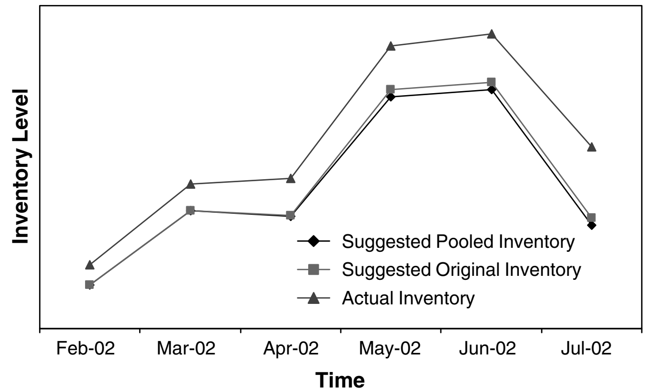

Figure 11: Using our decision-support system and modifying badge 16 to serve as both badge 14 and 16 would help ABC to reduce its total inventories by 19.3 percent.

Conclusion

Our system that combines forecasting techniques, inventory models, and optimization programs could help ABC to manage its inventory. In our analysis, we showed that ABC could have reduced inventory and saved costs had it used our system during the six-month validation period. To our knowledge, our system is the first to integrate various operations-research techniques for managing refurbished products with uncertain demand, uncertain return, and supplier constraints. We hope that our work will motivate others to develop systems that integrate different operations-research techniques that enable managers to handle challenging problems.

Although we developed our system to manage ABC's inventory of the refurbished products, it could easily be extended to handle other inventory problems that include refurbished or recycled products. For example, Chep, a wooden-pallet-leasing company, leases wooden pallets to such manufacturers as Campbell Soup Company. Usually, Campbell Soup uses these pallets to ship its canned goods to distributors. Because of time lags in the supply chain, Chep must send newly refurbished pallets to Campbell Soup before it can collect the old pallets from various distributors. As another example, hospitals that lease medical pumps for dispensing intravenous medicine to home-care patients usually deliver refurbished pumps to the patients before collecting the old pumps for recycling. In both of these cases and many others, organizations could use our system to manage inventory in a cost-effective manner while providing targeted customer service.

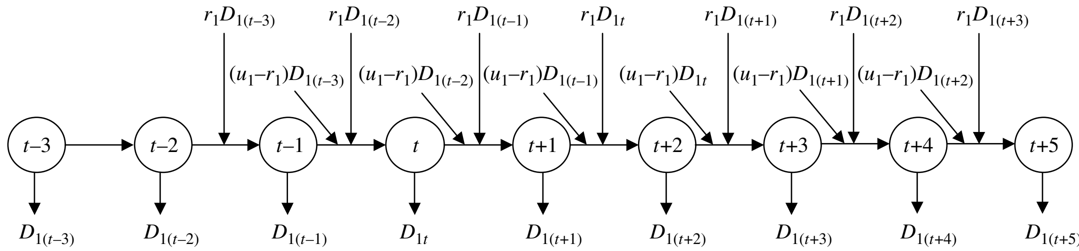

Figure 12: Demand and return flows for a customer with a recording cycle of one period.

Appendix

Return Forecast

Let D_{it} and R_{it} represent the demand and return of customer type i in period t, respectively. Customers return a certain percent of used badges within one month and almost all within two months. For customer type i, we define r_i and $(u_i - r_i)$ as the percentage of the reusable old badges being returned to ABC during the first month and the second month, respectively. We let $r_i < u_i$ and $u_i < 100\%$.

Single Customer with a Recording Cycle of One Month

ABC ships $D_{i(t-2)}$ badges to customer group 1 with a recording cycle of one month at the beginning of month $t-2$. Because customer group 1 has a recording cycle of one month, these badges are due back to ABC at the beginning of month $t-1$. However, because of a delayed return process at the customer's site, $r_1D_{1(t-2)}$ badges are returned to ABC during month $(t-1)$ and $(u_1 - r_1)D_{1(t-2)}$ are returned to ABC during month t (Figure 12).

R_{1t}'s are obtained from the following equation:

$$R_{1t} = r_1D_{1(t-1)} + (u_1 - r_1)D_{1(t-2)}.$$

Multiple Customers

The three customer types have different recording cycle times of one month, three months, and six months, with the following equations showing the demand patterns of these three customer types (Figure 13):

Type 1 requires new badges every month:

$$D_{1t} > 0 \quad \text{for every } t.$$

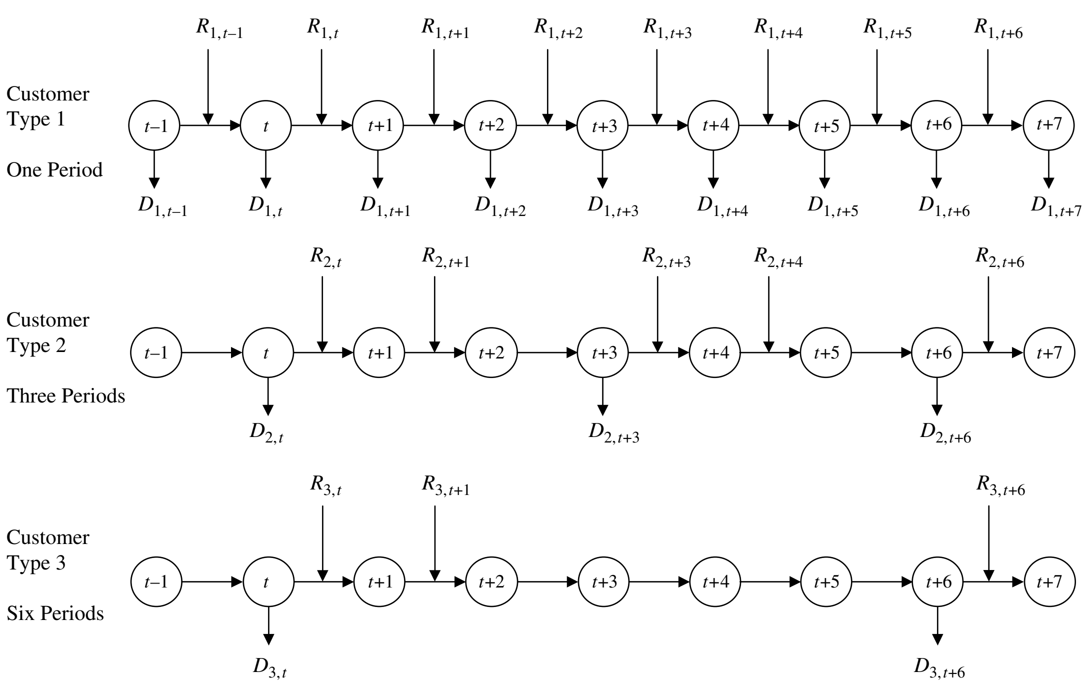

Figure 13: Demand and return flows for three customers with different recording cycle times of one month, three months, and six months.

Type 2 requires new badges every three months:

$$D_{2t} > 0 \quad \text{if } t \text{ is a multiple of } 3,$$
$$D_{2t} = 0, \quad \text{otherwise.}$$

Type 3 requires new badges every six months:

$$D_{3t} > 0 \quad \text{if } t \text{ is a multiple of } 6,$$
$$D_{3t} = 0, \quad \text{otherwise.}$$

We calculate returns from customer type 2 as follows:
Let t be a multiple of 3,

$$R_{2t} = r_2 D_{2(t-3)},$$
$$R_{2(t+1)} = (u_2 - r_2) D_{2(t-3)},$$
$$R_{2(t+2)} = 0.$$

Similarly, we calculated returns from customer type 3 as follows:
Let t be a multiple of 6,

$$R_{3t} = r_3 D_{2(t-6)}, \qquad R_{3(t+3)} = 0,$$
$$R_{3(t+1)} = (u_3 - r_3) D_{3(t-6)}, \qquad R_{3(t+4)} = 0,$$
$$R_{3(t+2)} = 0, \qquad R_{3(t+5)} = 0.$$

The total return in any month is the sum of returns from all customer types. So, if R_t represents the total return in month t, we calculate it as follows:

$$R_t = R_{1t} + R_{2t} + R_{3t}.$$

Integer Program for the Optimal-Ordering Module

Indices

$j \in \{1, 2, \ldots, M\}$: badge types.
$t \in \{1, 2, \ldots, T\}$: time index.

Decision Variables

Z_{jt}: number of badge type j to be ordered in period t.
I_{jt}: level of badge type j inventory at the end of period t.

Parameters

Q_{jt}: planned order quantity of badge type j in period t, determined in the planned-ordering module.
C_t: supplier capacity in period t.
K_t: fixed ordering cost in period t that ABC incurs when it places an order with the supplier.
c_{jt}: unit purchasing cost of badge type j in period t.
h_{jt}: unit inventory-holding cost of badge type j in period t.

Let $\delta(z)$ be an indicator function such that $\delta(z)$ equals 1 when $z > 0$ and 0, otherwise.

Integer Program Formulation

$$\text{Min} \sum_{t=1}^{T} K_t \delta\left(\sum_{j=1}^{M} Z_{jt}\right) + \sum_{t=1}^{T}\sum_{j=1}^{M} (c_{jt} Z_{jt} + h_{jt} I_{jt}),$$

$$Z_{jt} + I_{j(t-1)} = Q_{jt} + I_{jt} \quad \text{for } j = 1, \ldots, M, \; t = 1, \ldots, T, \tag{1}$$

$$\sum_{j=1}^{M} Z_{jt} \le C_t \quad \text{for } j = 1, \ldots, M, \tag{2}$$

$$I_{jt}, Z_{jt} \ge 0 \quad \text{for } j = 1, \ldots, M, \; t = 1, \ldots, T. \tag{3}$$

The objective of the program is to minimize the total ordering cost, variable cost, and inventory-holding cost. The first set of constraints is the inventory balance equations. The second set of constraints ensures that the supplier's capacity will not be violated. The third set of constraints is for the nonnegativity of the decision variables.

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Sander C. Perle, Vice President, Technical Operations, writes: "Thank you for giving me the opportunity to review the paper 'An Integrated Planning System for Managing the Refurbishment of Thermoluminescent Badges' by Murat Bayiz and Christopher S. Tang.

"I think they've done an outstanding job in the paper of defining our environment and the challenges associated with managing the flow of reusable thermoluminescent badges. As we had discussed in the early meetings, it has been a challenge to plan the future operations due to difficulties in estimating future demand and returns.

"The models that they developed are critical in defining a systematic way to monitor demand and return of thermoluminescent badges and managing our inventories while maintaining high customer service standards. The purchase-planning model took into consideration important supplier related factors such as long purchasing lead time and limited supplier capacity. I truly believe that the deployment of these models at our organization will excel our operations and help us to maintain our leading role in the dosimetry services industry."