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PENALTY ENFORCEMENT OR COST REDUCTION – WHICH APPROACH BETTER IMPROVES SUPPLIER PROCESS YIELD?

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ABSTRACT

Retailers have been increasing standards for suppliers in regard to demand-fulfillment performance. To discourage partial deliveries due to unacceptable, defective products, retailers can unilaterally back-charge the supplier a penalty or collaboratively improve the supplier's production process yield and reduce the supplier's quality investment expenditure. In this study, we create an analytical model that compares the retailer's penalty-enforcement and cost-reduction approaches in which the supplier must optimize its production process yield to minimize the total expected cost. The findings indicate that using either approach can induce the supplier to improve process yield. The simulation results show that the cost-reduction approach may require less effort than the penalty-enforcement approach to attain the same level of quality improvement.

1 INTRODUCTION

In the retail industry, product availability is often the retailers' top priority. Therefore, retailers are constantly under pressure to identify and adopt approaches that can effectively and efficiently improve their suppliers' demand fulfillment performance. Retailers cannot afford to take a back seat when suppliers encounter production process quality issues, because those issues can ultimately affect retailers' product availability. In this study, we compare two approaches that retailers can take to improve suppliers' production process yield, as well as assess the relative risks involved with either approach so that retailers can make robust decisions when faced with uncertainty.

Historically, buying firms can improve the production process yield and reduce the product defect rate by involving the supplier in the design process so that fewer nonconforming units are produced (Zhu et al. 2007). In the retail industry, retailers have assumed the role of quality leader and have pressured manufacturers to follow practices that lead to improved production quality (Jonas and Roosen 2005; Chaudhuri and Kostov 2018). Retailers seeking high profit margins can impose high standards and quality requirements on their suppliers (Ter Braak et al. 2013). Retailers can also form partnerships with suppliers to improve operations, which can be measured by product quality and the number of partial orders (Mentzer et al. 2000). Retailers that share information and collaborate with their suppliers on business processes are likely to have a better service (Hammer 2001). Many other benefits of collaboration between supply chain partners have been studied extensively (Simatupang and Sridharan 2005; Soosay et al. 2008). In particular, Croxton et al. (2001) pointed out that the supplier development strategy is important for analyzing product quality and examining the root causes of quality problems. For example, Walmart developed guidelines for sharing process improvement benefits with Procter & Gamble and split the cost savings (Croxton et al. 2001). Therefore, retailers can use a collaborative cost-reduction approach to improve their suppliers' production process yield.

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Despite the opportunity to reduce costs and enhance quality by partnering with suppliers, retailers have increasingly shifted their attention to contractualizing demand-fulfillment requirements to address the issue of partial shipments. For example, if unacceptable, defective products are found in the shipments such that the delivery cannot fully satisfy the retailer's order quantity, then the supplier could be back-charged a hefty service level penalty (Chen 2018). Because many retailers have implemented this kind of chargeback in their service level agreements, suppliers with process yield issues could lose a significant amount of money to the service level penalty. Walmart has recently imposed a chargeback of 3% of the cost of delayed goods on any non-compliant suppliers (Nassauer and Smith 2018). Target has increased its chargeback for a similar cause to 5% while disallowing any grace period extending before and after the requested delivery (Boyle 2017; Bolduc 2018). Other retailers have launched similar initiatives as well to ensure that their suppliers can reduce variability in product availability (Gasparro et al. 2017; Gilmore 2018). Using a penalty-enforcement approach to manage inbound logistics has gained popularity among retailers (Smith and Nassauer 2019).

Therefore, the effectiveness of the two approaches on improving production process yield has been supported by the empirical evidence presented in the literature. Theoretical evidence that the retailer's investment-based and penalty-based approaches can effectively improve the supplier's production process yield can be found in Lee and Li (2018) as well. Nonetheless, improving process yield issues does not come without effort. Taking the cost-reduction or penalty-enforcement approach, the retailer facing production process yield issues must make efforts either by increasing the penalty amount on the supplier or lowering the quality improvement cost for the supplier. For example, under the cost-reduction approach, joint efforts between the supplier and the retailer could be conscious managerial actions, process improvement projects, defect prevention efforts, and personnel training (Li and Rajagopalan 1998; Krause 1999; Zhu et al. 2007). Under the penalty-enforcement approach, the efforts could be managerial endeavors to ensure the supplier is compliant. For example, when the automotive retailer Pep Boys asked its suppliers to pay a penalty for product availability issues, the suppliers complained to Pep Boys' buyers, and most of the time, the charges were reversed (Douglas 2006).

However, to attain the same level of defect rate improvement, are the required efforts under each approach the same? In this study, the two approaches are said to have different efficiencies if the required efforts for achieving the same level of defect rate improvement are different. Moreover, the approach that requires less effort to achieve the same level of improvement is the one with higher efficiency. The literature offers little insight into the efficiency of the two approaches in achieving the retailer's goal of improving the supplier's production process yield. Therefore, our research question is, *which of the retailer's approaches—penalty enforcement or cost reduction—has a better efficiency in improving the supplier's production process yield?* Not many studies explicitly compare the efficiency of the two approaches. To this end, we first solve for the supplier's optimal production process yield under which the supplier's total expected cost is minimized. Subsequently, we conduct a what-if analysis and simulation experiments to illustrate the efficiency of the retailer's approaches. Note that assessing the efficiency of the *individual* approaches is not within the scope of this study. Instead, the main focus of this study is to *compare* the efficiencies of the approaches. The remainder of this article is organized as follows: Section 2 presents a simple supply chain model. In Section 3, we present the Monte Carlo simulation analyses and results. In Section 4, we conclude with a summary of our findings.

2 SUPPLY CHAIN MODELING

To answer the research question, we model a supply chain in which a single retailer and supplier have a service level agreement (Chen and Thomas 2018). In this decentralized supply chain, the retailer decides (a) the investment in the supplier's process yield improvement, thereby reducing the supplier's cost, or (b) the increment of the service level penalty. The retailer's decision directly affects the supplier's total expected cost in relation to the service level penalty and process yield investment, and the supplier responds with the optimal process yield that minimizes the total expected cost.

2.1 Process Yield

In the typical inventory model, the production process is often implicitly assumed to be perfect and yield no defective products. In reality, defective products can exist in a production lot due to imperfect production processes (Li and Rajagopalan 1998). Porteus (1986) established the formula of defective product quantity as a function of the production lot size and probability that the production process becomes "out of control" and begins to produce a defective product. Marcellus and Dada (1991) presented a production process model in which the decision makers can decide the investment in production quality to reduce defective products. Hong and Hayya (1995) provided a general solution procedure that examines the optimal allocation of investments between process yield improvement and setup cost reduction. These studies do not consider the role of a buying firm (i.e., retailer) in the decision-making process.

In this study, the retailer has a stochastic demand quantity X of a single product and orders the product from the supplier prior to a selling season. The supplier produces the product after receiving the retailer's order and delivers the production quantity to the retailer at the beginning of the selling season. Based on Porteus (1986), we assume a positive defect rate θ in the model and $R = X - Y$, where R and Y denote the expected number of defective products and the expected number of conforming products in a production lot, respectively, and θ means that the production process has the probability of θ to go out of control when each product is being produced. For any defective products, the supplier would have no time or resources to rework those units. Figure 1 shows that the manufacturing process essentially is a two-state Markov chain (MC) during the production run: The state 0 denotes the machine produces conforming products, and the absorbing state 1 denotes the machine produces defective products. The machine always starts with the in-control state 0 and can change state to 1 at any time during production.

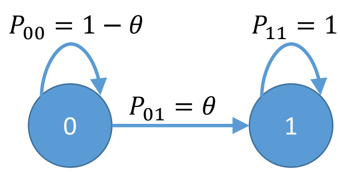

Figure 1: Transition diagram for the states of a machine that produces products. The state 0 denotes the machine is in good working order, and 1 denotes the machine is in an out-of-control state.

For any given X, the possible number of defective products is $r = X - i$ with probability $\Pr(r = X - i) = \theta(1-\theta)^i$ for $i \in [0, X]$, respectively. There would be no defective products if $X = 0$ ($\theta = 0$ is unrealistic and is not considered in this study). Furthermore, R can be derived as follows (Porteus 1986):

$$\begin{aligned}
R &= \sum_{i=0}^{X} r \cdot \Pr(r = X - i) \\
&= \sum_{i=0}^{X} (X - i) \cdot \theta(1-\theta)^i \\
&= \theta \left[X \left(1 + (1-\theta) + (1-\theta)^2 + (1-\theta)^3 + \cdots + (1-\theta)^X \right) \right. \\
&\qquad \left. - \left((1-\theta) + 2(1-\theta)^2 + 3(1-\theta)^3 + \cdots + X(1-\theta)^X \right) \right] \\
&= \theta \left[X \cdot \frac{1-(1-\theta)^{X+1}}{1-(1-\theta)} - \frac{\left[(1-\theta) - (X+1)(1-\theta)^{X+1} + X(1-\theta)^{X+2}\right]}{(1-(1-\theta))^2} \right] \\
&= X - \frac{(1-\theta)\left[1-(1-\theta)^X\right]}{\theta}.
\end{aligned}$$

Porteus (1986) stated that R is a strictly increasing, strictly convex function of X. In this study, we assume the supplier resolves the production quality issue at the root cause instead of taking a shortcut, for example, overproducing to offset the potential defective quantity. Moreover, we prove that R is an increasing function of θ for any given $X \geq 0$ in the Appendix A. Next, we express the expected value of R as

$$\mathbb{E}[R] = \sum_{x=0}^{N} \left[x - \frac{(1-\theta)\left[1-(1-\theta)^x\right]}{\theta} \right] \Pr(X = x).$$

For analytical tractability, we let $N \gg 0$, and X follows an exponential distribution with mean $1/\lambda$. Therefore,

$$\begin{aligned}
\mathbb{E}[R] &\sim \int_{x=0}^{N \gg 0} \left[x - \frac{(1-\theta)\left[1-(1-\theta)^x\right]}{\theta} \right] f_X(x)dx \\
&\sim \int_{0}^{\infty} \left[x - \frac{(1-\theta)\left[1-(1-\theta)^x\right]}{\theta} \right] \lambda e^{-\lambda x} dx \\
&= \left[-xe^{-\lambda x} - e^{-\lambda x}\left(1 + \frac{1}{\lambda} - \frac{1}{\theta}\right) - \frac{\lambda e^{-\lambda x}(1-\theta)^{x+1}}{\theta(\lambda - \ln(1-\theta))} \right] \Bigg|_{0}^{\infty} \\
&= \underbrace{\frac{1}{\lambda}}_{\mathbb{E}[X]} - \underbrace{\left[-\frac{(1-\theta)\ln(1-\theta)}{\theta(\lambda - \ln(1-\theta))} \right]}_{\mathbb{E}[Y]}.
\end{aligned}$$

In practice, defect rates tend to be close to zero. For example, the concept of the popular Six Sigma standard suggests a goal of 3.4 defects per million opportunities to produce some feature of a part expected to be free of defects, or 99.99966% process yield (Linderman et al. 2003). For a small θ, the Taylor series for $\ln(1-\theta)$ is approximately equal to $-\theta$. Therefore, we can further simplify $\mathbb{E}[R]$ as follows:

$$\mathbb{E}[R] \sim \frac{1}{\lambda} - \frac{(1-\theta)}{\lambda+\theta}.$$

2.2 Expected Costs

One of the two costs considered in the model is the production process yield investment, hereafter "process yield cost," which enables the supplier to *decrease* the defect rate. We use $I(\theta)$ to denote the process yield cost. Intuitively, $\mathbb{E}[I(\theta)]$ is a decreasing function of θ for all θ less than or equal to θ_0, where θ_0 is the initial defect rate before any improvement. To formulate $\mathbb{E}[I(\theta)]$, we consider the logarithmic cost function established by Porteus (1985): $\mathbb{E}[I(\theta)] = a - c_q \ln(\theta)$, where a and c_q are some positive constants. Clearly, a smaller defect rate requires a larger production process yield investment. Without loss of generality, $\mathbb{E}[I(\theta_0)]$ can be normalized to 0. As a result,

$$\mathbb{E}[I(\theta)] = c_q \ln\left(\frac{\theta_0}{\theta}\right). \quad (1)$$

We can see that $\mathbb{E}[I(\theta)]$ is a decreasing, convex function of θ. Conventionally, c_q has been interpreted as the inverse of the percentage decrease in θ per dollar increase in $\mathbb{E}[I(\theta)]$ (Ouyang et al. 2007; Dey and Giri 2014; Sarkar et al. 2015). In this study, we call c_q the *quality coefficient*. The retailer can collaborate with the supplier and contribute to the improvement of the production process such that the supplier would have a smaller c_q, thereby decreasing $\mathbb{E}[I(\theta)]$. If the cost-reduction approach was the only approach available to the retailer, then the supplier facing the objective function $\mathbb{E}[I(\theta)]$ would trivially set a maximum θ_0 to minimize the expected process yield cost. On the other hand, holding everything else constant, decreasing c_q would cause the supplier to decrease θ.

The other cost considered in the model is the service level penalty. Under a service level agreement with 100% target fill rate, the retailer may charge the supplier a *service level penalty* $P(\theta)$ upon receiving a shipment that contains defective products (Chen 2018). While there are many different types of service level penalties, we focus on the penalty that linearly increases with the number of defective units (Sieke et al. 2012; Chen and Thomas 2018). We formulate the expected penalty as follows:

$$\begin{aligned}\mathbb{E}[P(\theta)] &= c_p\mathbb{E}[R] \\ &= \frac{c_p}{\lambda} - \frac{c_p(1-\theta)}{\lambda+\theta}.\end{aligned}$$

We can see that $\mathbb{E}[P(\theta)]$ is an increasing, concave function of θ. In this study, we call c_p the *penalty coefficient*, which denotes the cost per unit of the defective product in a production lot. The retailer can update the contract terms to increase c_p, thereby increasing $\mathbb{E}[P(\theta)]$. We assume that the retailer increases c_p for no other purpose than to motivate the supplier to improve θ: The penalty-funded money $P(\theta)$ is said to offset the costs of disrupted operations and lost sales (Chen 2018). If the penalty-enforcement approach was the only approach available to the retailer, then the supplier facing the objective function $\mathbb{E}[P(\theta)]$ would trivially set a minimum θ to minimize the expected penalty cost. On the other hand, holding everything else constant, increasing c_p would cause the supplier to decrease θ.

2.3 Optimal Yield

The total expected cost of the service level penalty and process yield cost as the objective function of a cost-minimization problem facing the supplier can be written as follows:

$$\mathbb{E}[G(\theta)] = \mathbb{E}[P(\theta)] + \mathbb{E}[I(\theta)].$$

Because no improvements to the production process yield can be made while production is ongoing, the supplier must determine θ before receiving the retailer's order. As a result, the supplier essentially faces the newsvendor's problem (Cachon 2003). That is, the supplier must choose a process yield that minimizes the total expected service level penalty and process yield cost in advance of the retailer's order. While not capturing every relevant cost in practice, this stylized expression of $\mathbb{E}[G(\theta)]$ accounts for the major risks of setting the process yield too high or too low. Since $\mathbb{E}[P(\theta)]$ and $\mathbb{E}[I(\theta)]$ are continuous and differentiable on the interval of $\theta \in (0,1]$, there may exist an optimal process yield in terms of the defect rate θ^* that minimizes the total expected cost $\mathbb{E}[G(\theta)]$. Given the optimal process yield, the retailer can then conduct a what-if analysis to investigate the implications of varying its effort on θ^*, where the retailer's effort under the approaches is defined as the percentage increase of c_p or decrease of c_q. In this study, we assume that the managerial resources for the efforts of successfully decreasing c_q and of increasing c_p are the same. As a result, the retailer has no preference between increasing c_p and decreasing c_q.

To find θ^*, we derive the first-order condition of $\mathbb{E}[G(\theta)]$ with respect to θ:

$$\begin{aligned}\frac{\partial\mathbb{E}[G(\theta)]}{\partial\theta} &= -\frac{c_q}{\theta} + \frac{c_p}{\lambda+\theta} - \frac{c_p(\theta-1)}{(\lambda+\theta)^2} \qquad (2)\\ \Rightarrow \theta^* &= -\lambda + \frac{1+\lambda}{2}\left[\rho - \sqrt{\rho^2 - \frac{4\rho\lambda}{(1+\lambda)}}\right] \\ &> -\lambda + \frac{1+\lambda}{2}\left[\rho - \sqrt{\rho^2 - \frac{4\rho\lambda}{(1+\lambda)} + \left(\frac{2\lambda}{1+\lambda}\right)^2}\right] = 0 \\ \Rightarrow \frac{\partial\theta^*}{\partial\rho} &= \frac{1+\lambda}{2}\left[1 - \frac{\left(\rho - \frac{2\lambda}{1+\lambda}\right)}{\sqrt{\rho^2 - \frac{4\rho\lambda}{1+\lambda}}}\right] < \frac{1+\lambda}{2}\left[1 - \frac{\left(\rho - \frac{2\lambda}{1+\lambda}\right)}{\sqrt{\rho^2 - \frac{4\rho\lambda}{1+\lambda} + \left(\frac{2\lambda}{1+\lambda}\right)^2}}\right] = 0,\end{aligned}$$

where $\rho = c_p/c_q$. The approach that requires less effort to achieve the same production process yield would be viewed as having higher efficiency. The negative first-order condition of θ^* with respect to ρ suggests that the greater ρ is, the smaller θ^* the supplier would settle. More important, the same amount of effort on c_p and on c_q will result in different levels of impact on θ^*, holding everything else constant. For example, a 10% increase in c_p can make ρ 10% greater, but a 10% decrease in c_q can make ρ 11.11% greater. Therefore, we find the answer to the research question to be as follows: *The cost-reduction approach is more efficient than the penalty-enforcement approach in improving the supplier's production process yield.* Please see the proof that θ^* is the optimal solution in the Appendix B.

3 MONTE CARLO SIMULATIONS

The goal of this section is to numerically assess and illustrate the impact of using the retailer's two approaches on improving the supplier's process yield while varying the cost-reduction or penalty-enforcement efforts. In applying the law of large numbers, we generate 10^6 random demand quantities using the inverse transformation of $U(0,1)$ random numbers to simulate the supplier's productions and resultant number of defective products given each set of experimental input values. The retailer's demand quantity follows the Poisson distribution, which is a common distribution for simulating discrete demand (Song and Zipkin 1993).

3.1 Fill Rate

First, we evaluate an appropriate initial defect rate θ_0 to use in the following numerical analysis. Particularly, we would like to use the initial defect rate which allows expected fill rates to be greater than 90%. In general, fill rates are computed as the quantity of non-defective products divided by the demand quantity. Specifically, the expression of the single-period fill rate is $\alpha(\theta) = 1 - R/X$. Therefore,

$$\begin{aligned}\mathbb{E}[\alpha(\theta)] &= 1 - \mathbb{E}\left[1 - \frac{(1-\theta)\,[1-(1-\theta)^x]}{x\theta}\right] \\ &= \sum_{x=0}^{N}\left[\frac{(1-\theta)\,[1-(1-\theta)^x]}{x\theta}\right]\Pr(X=x).\end{aligned}$$

Nevertheless, Thomas (2005) pointed out that inventory managers tend to operate under the impression that they need to meet or exceed the infinite-horizon expression of fill rate:

$$\begin{aligned}\frac{\mathbb{E}[Y]}{\mathbb{E}[X]} &= -\frac{\lambda(1-\theta)\ln(1-\theta)}{\theta(\lambda-\ln(1-\theta))} \\ \lim_{\theta\to 0^+}\frac{\mathbb{E}[Y]}{\mathbb{E}[X]} &= \left.\frac{\lambda\ln(1-\theta)+\lambda}{\lambda-\ln(1-\theta)+\theta/(1-\theta)}\right|_{\theta=0^+} = 1.\end{aligned}$$

Figure 2 shows the single-period and infinite-horizon fill rate distributions based on the Poisson demand with mean 100 and a range of θ_0 from 0.0004 to 0.0256. Because the realized demand quantities are about 100 units, there are on average 10^8 individual products in total being produced in every simulation trial. Both the expected single-period and infinite-horizon fill rates drop as the defect rate increases, and the expected fill rates are greater than 90% only when $\theta_0 = 0.0004$. Therefore, we choose $\theta_0 = 0.0004$ as the input for the following simulation experiments.

3.2 Process Yield

Given $\theta_0 = 0.0004$, we now illustrate the convexity of the supplier's total expected cost under various means of Poisson distribution for simulating different retailer demands. Specifically, we let the expected retailer demand range from 60 to 120, and we set $c_p = c_q = 8$ to better visualize the results. Figure 3

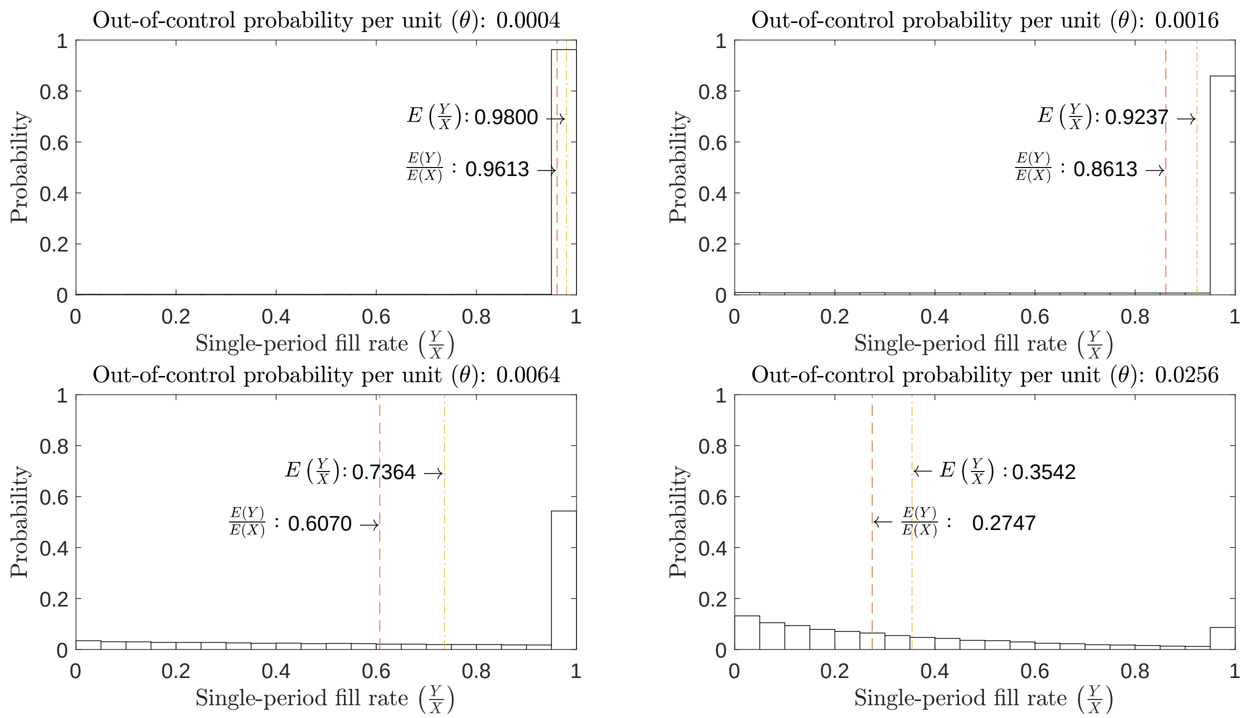

Figure 2: The 0.0004 defect rate allows the expected single-period and lone-run fill rates to stay above 90%, a rather practical target fill rate in the retail industry.

shows the supplier's expected service level penalty, process yield cost, and total cost. Holding c_q constant, the expected process yield cost curves remain the same across the four panels in the figure. Holding c_p constant, the greater the mean of the retailer's demand, the greater the impact of the service level penalty on the supplier's expected cost, illustrating that the defect rate is a strictly increasing function of demand quantity (Porteus 1986). We replicate a similar impact by varying c_p while holding the expected demand constant. The dash lines in the figure intuitively illustrate that the expected cost-minimizing defect rate (θ^*) decreases as the impact of the service level penalty increases.

3.3 Efficiency Comparison

Given $\theta_0 = 0.0004$, we now vary c_p, c_q, or the expected demand and examine their respective impacts on θ^*. For fair comparisons, c_p must be the same as c_q so that any percentage increment and reduction of c_p and c_q, respectively, would be the same as well. We continue to use $c_p = c_q = 8$ for this illustration. Figure 4 shows the impacts of the penalty cost (c_p) increment or quality expenditure (c_q) reduction (as a percentage) on the supplier's optimal process yield in terms of the defect rate (θ^*). Clearly, the optimal expected cost-minimizing defect rate drops faster under the process yield cost reduction than under the service level penalty increment. Therefore, collaboratively reducing the supplier's process yield cost tends to have a greater efficiency than unilaterally increasing the service level penalty. This finding is in line with Zhu et al. (2007) in that the buyer's (retailer's) proactive involvement can have a positive impact on the profits of both parties and on the supply chain as a whole.

One may argue that the managerial resource for the effort of attaining some percentage of process yield cost reduction could be greater than the managerial resource for the effort of attaining the same percentage of service level penalty increment. For example, given Poisson demand with mean 60 (top-left panel in Figure 4), the minimum c_p to attain $\theta^* = 0.00024$ has to be 130% of its initial value, whereas the maximum c_q to attain the same optimal process yield has to discount 60% of its initial value. To

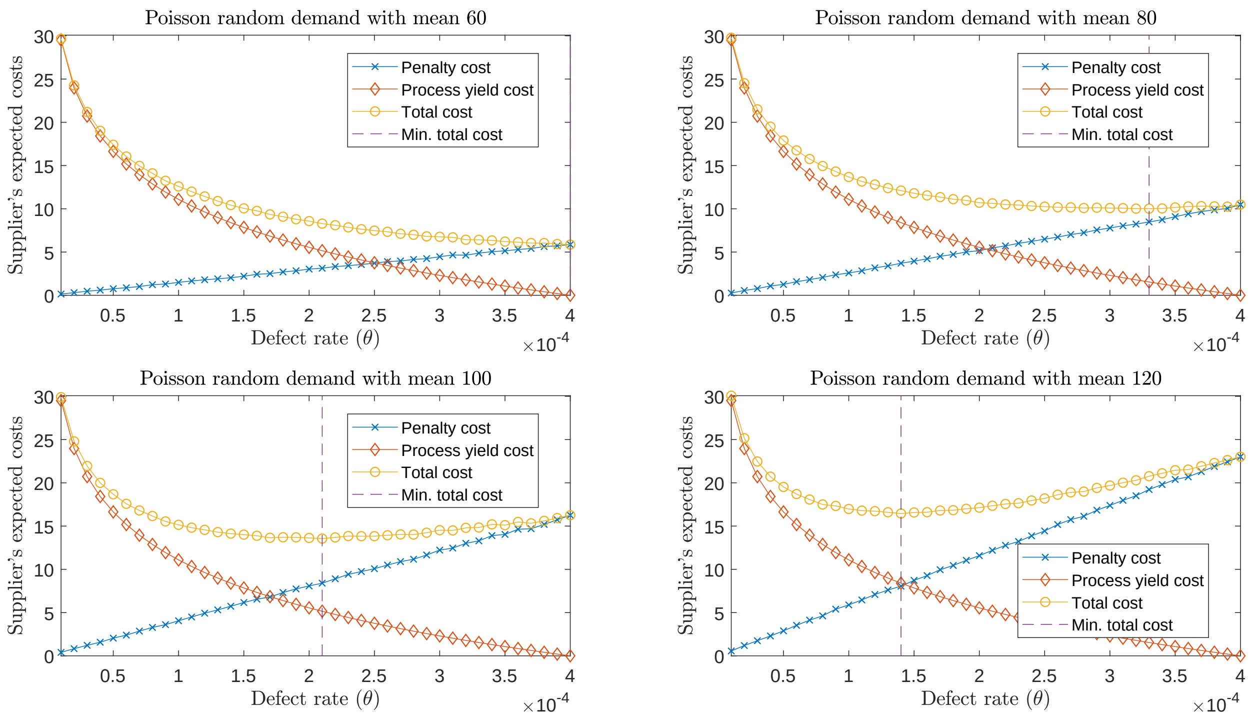

Figure 3: Increasing the production lot size increases the expected number of defective products; increasing the service level penalty decreases the defect rate.

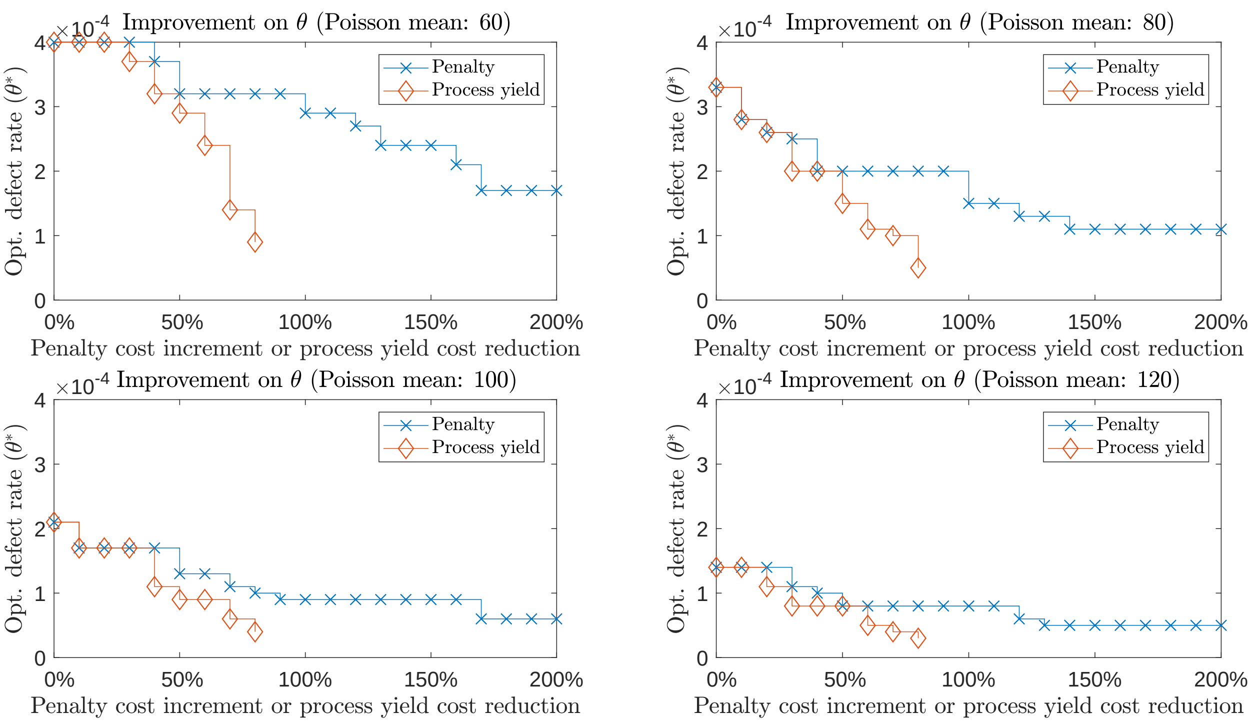

Figure 4: Collaboratively reducing the supplier's process yield cost induces the desired demand-fulfillment performance more so than unilaterally increasing the supplier's service level penalty cost.

address this practical consideration that the required managerial resource for the efforts to attain the same process yield improvement could be different between the approaches, we define the c_q *markup factor* as the minimum penalty coefficient increment divided by the maximum quality coefficient reduction, given the same process yield improvement. For example, the c_q markup factor given $\mathbb{E}[X] = 60$ and $\theta^* = 0.00024$ is 2.1667. That is, as long as the managerial resource for the effort of attaining 60% c_q reduction is not as much as 2.1667 times the managerial resource for the effort of attaining 130% c_p increment, the finding (i.e., reducing the process yield cost is more efficient than increasing the service level penalty in improving demand-fulfillment performance) still holds. Figure 5 indicates that unless adjusting c_q is significantly more strenuous (or requires larger managerial resource) than adjusting c_p, the retailer should take the c_q approach rather than the c_p approach to induce better demand-fulfillment performance from the supplier, especially when aiming for a considerable quality improvement.

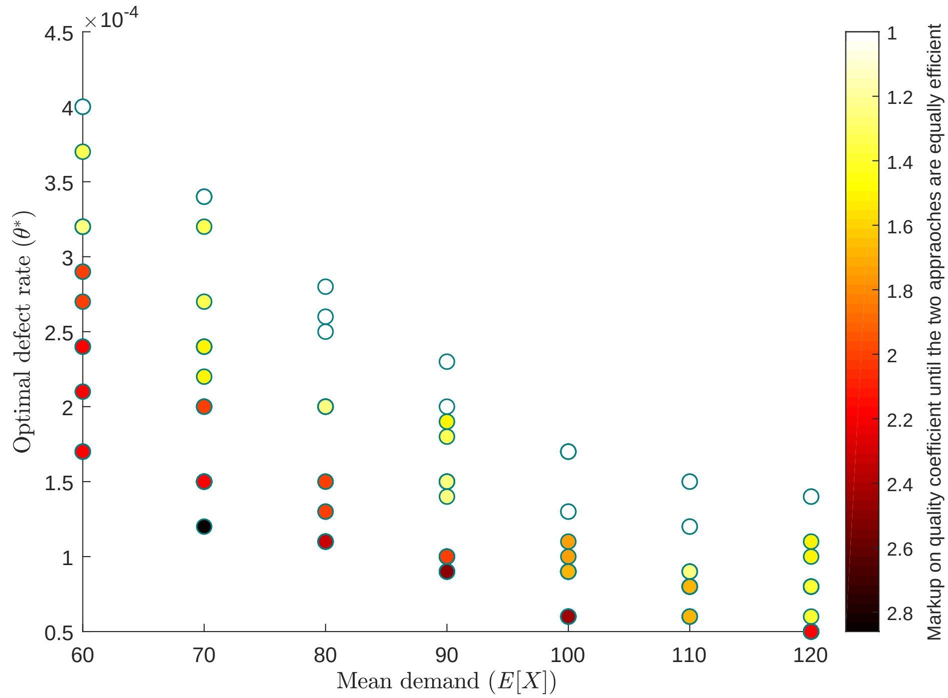

Figure 5: Circle shades denote that reducing the process yield cost is many times more efficient than increasing the service level penalty to attain the same optimal process yield improvement.

3.4 Limitations and Extensions

The challenges encountered in this study mainly lie in conceptualizing the business problem and applying appropriate theoretical models and simulation procedures to address the problem. The generality of the findings is limited by the model assumptions. For future research, one may consider distributions other than exponential or Poisson for simulating the retailer's demand. Another possibility might be to consider a more complex MC (e.g., three-state MC where it is possible to leave any state) to model the event of defect products. With any of these changes, the analytical results currently derived in this study will need to be re-examined, and simulation will play an even more important role in assessing the risks.

4 CONCLUSION

Production processes are rarely perfect in practice and hence can yield defective products. Upon receiving, defective products would be rejected by the retailer, negatively affecting the retailer's product availability and profitability. To ensure that the supplier's shipments can be on time and fulfill the order quantity, the retailer can increasingly penalize the supplier for partial deliveries or help the supplier improve its production process yield while collaboratively reducing the supplier's process yield improvement cost. While studies suggest that either approach can induce better demand-fulfillment performance from the supplier, this article fills a void in the literature by comparing the efficiency of the two approaches in terms of the retailer's effort to attain the same level of process yield improvement. Focusing on the retail industry, this study contributes to the literature by informing retailers that the penalty-enforcement approach is less efficient than the cost-reduction approach in achieving the desired production process yield. The finding is aligned with the experts' narratives that supply chain partners should use more carrots (e.g., collaboration) and less sticks (e.g., penalty) in the supply chain (Vitasek 2016). Since both the supplier and retailer should have the common incentive to invest in quality-improvement efforts, collaboratively improving the supplier's production process yield shall be a better way to achieve long-term health of the supply chain.

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APPENDIX A: INCREASING FUNCTION R

$$\frac{\partial R}{\partial \theta} = \frac{1-(1-\theta)^X(1+\theta X)}{\theta^2}. \tag{3}$$

Eq. (3) suggests that the first-order condition of R with respect to θ switches sign only once at $\theta = 0$. Considering $0 < \theta \leq 1$, we see that if $\theta = 1$, then the first-order condition is equal to 1; if θ is close to 0, then we use L'Hôpital's rule to determine the limit:

$$\begin{aligned} \lim_{\theta \to 0^+} \frac{\partial R}{\partial \theta} &= \lim_{\theta \to 0^+} \frac{X(1+X)(1-\theta)^{X-1}}{2} \\ &= \frac{X(1+X)}{2} > 0. \end{aligned}$$

Because $\partial R/\partial \theta$ is strictly positive for all feasible θ, we prove that R is an increasing function of θ. □

APPENDIX B: OPTIMAL SOLUTION θ^*

For verification purpose, could the other root of Eq. (2) be the solution instead of θ^*? Let the other root of Eq. (2) be

$$\hat{\theta} = -\lambda + \frac{1+\lambda}{2}\left[\rho + \sqrt{\rho^2 - \frac{4\rho\lambda}{(1+\lambda)}}\right] > \theta^*.$$

A counter example for the argument that $\hat{\theta}$ is the solution is $\rho = 2$ and $\lambda = 0.01$, which results in $\hat{\theta} > 1$ and $\partial^2\mathbb{E}[G(\hat{\theta})]/\partial\theta^2 < 0$. Furthermore, we follow the assumption that the retailer is indifferent between

c_p and c_q and proceed with the following proof using $c = c_p = c_q$:

$$\begin{aligned}\frac{\partial^2 \mathbb{E}[G(\theta^*)]}{\partial \theta^2} &= \frac{c}{\theta^{*2}} - \frac{2c(1+\lambda)}{(\lambda+\theta^*)^3} \\ &= c \cdot \frac{\lambda^3 + 3\lambda^2\theta^* + (\lambda-2)\theta^{*2} + \theta^{*3}}{\theta^{*2}(\lambda+\theta^*)^3},\end{aligned}$$

and the numerator (that determines the sign of $\partial^2\mathbb{E}[G(\theta^*)]/\partial\theta^2$) is

$$\frac{3\lambda^2 + (1+\lambda)(1-2\lambda)\sqrt{(1-3\lambda)(1+\lambda)} + 2\lambda - 1}{2}.$$

The extreme values (at the boundaries and roots of the first derivative) of this continuous and differentiable function of λ are positive. Thus, we conclude that θ^* minimizes the supplier's total expected cost. □

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