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AI Automation and Retailer Regret in Supply Chains

Meng Li
C.T. Bauer College of Business, University of Houston, Houston, Texas 77204, USA, mli@bauer.uh.edu

Tao Li*
Leavey School of Business, Santa Clara University, Santa Clara, California 95053, USA, tli1@scu.edu

Artificial intelligence (AI) has significantly changed the supply chain process. In this study, we study the effects associated with AI *automation* of the retailer's order decision in a decentralized supply chain comprising one supplier and one regretful retailer. In the absence of AI automation, the retailer has a regret bias in that it behaves as though considering the deviation between the realized demand and order quantity, when making an ex ante inventory decision. We find that if profit margins of the supply chain are high, regret bias drives the retailer to decline the supplier's contract, whereas, if profit margins are low, regret drives retailers to order more from the supplier. As a result, although the automation of retailer decision leads to a higher expected profit for a retailer that operates in a centralized vacuum, it nevertheless can be a negative force for a decentralized supply chain with either high or low profit margins. Perhaps more interestingly, as a retailer's decision becomes automatic, it is not destined to earn a higher expected profit. In the extreme, a lose-lose outcome can prevail in which automation potentially leaves both the retailer and supplier worse off.

Key words: managerial bias; human–machine reconcile; emotion; Industry 4.0; Artificial Intelligence
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*Corresponding author.

Excessive automation ... was a mistake. Humans are underrated.

— Tesla CEO, Elon Musk.

1. Introduction

Artificial intelligence (AI) *automation* is a key implication of the fourth industrial revolution, that is, Industry 4.0 (Olsen and Tomlin 2020). The potential payoffs of AI automation are enormous. Many firms have adopted automated systems to manage inventory replenishment decisions. For example, automated inventory replenishment systems often recommend order quantities to the retail store managers (Van Donselaar et al. 2010). Although this automated system effectively reduces decision bias of managers, interestingly, store managers might bypass the system, and manually decide orders (Fisher and Raman 2010).

In this study, we analytically explore how AI automation—replacing human managers with an optimally programmed ordering system—affects ordering decisions and expected profits of newsvendors and suppliers in supply chains governed by wholesale price contracts. The question of how human managers decide orders has attracted significant attention within operations management. The classical paper of Schweitzer and Cachon (2000) posits that newsvendors (retailers) attempt to minimize ex-post regret, thus explaining the famous pull-to-center effect in newsvendor experiments. In essence, regret is a negative emotion experienced when an individual learns that an alternative course of action would have resulted in a more favorable outcome.

We then develop a model that incorporates regret into the classical selling-to-newsvendor model. In our model, the supplier (*he*) leads by announcing a unit wholesale price to his newsvendor retailer (*she*), after which the newsvendor decides the quantity to purchase as stock at the start of her selling season. As a validation to the literature, we analytically show that in the single-newsvendor setting, the pull-to-center effect also exists. In addition, we show that the regret bias may drive a newsvendor to reject profitable contracts offered by her supplier.

Furthermore, we find that, unlike in a single-newsvendor setting, regret bias in a selling-to-newsvendor setting can lead to increased expected profits for the system. This implies that automation can hurt the system, depending on the market situation. For example, we show that if profit margin of the supply chain (i.e., the difference between the retail price and production cost) is relatively high, high levels of regret can benefit the supply chain consisting of a biased newsvendor and a supplier. Intuitively, under this condition, regret can be considered as a bias that drives the newsvendor to decline the supplier's contract. To avoid this rejection, the supplier must charge a relatively low wholesale price, providing a counterbalance to decentralization's drive to charge a high wholesale price (Spengler 1950). If profit margins are relatively low, regret bias can be a positive force for the supply chain, because under this condition, regret bias drives newsvendors to order more, providing a counterbalance to decentralization's drive to order less. Thus, in high and low margins, the net effect generates a potential to benefit the supply chain as a whole.

For more insights, we consider a baseline supply chain comprised of one newsvendor and one supplier, but managed by an unbiased central planner. In this setting, the supply chain as a whole would be worse off, if the unbiased central planner were to be replaced by a biased central planner; similarly, the supply chain would also be worse off, if no central planner was involved so that the two firms optimize their individual profits. However, if the central planner were to be removed and the newsvendor were to be replaced with a biased newsvendor, depending on the extent of regret bias, the total expected profit of the channel could potentially equal that of the baseline channel. In this sense, regret bias could be a force that coordinates a decentralized channel with its centralized counterpart, particularly when the profit margin is relatively low.

Given that both positive and negative interactive forces result from regret bias in a decentralized supply chain, we assess the effects of regret on the equilibrium outcomes of the supplier and the newsvendor. We find that the expected profits of the supplier and the newsvendor can be characterized as a function that is not decreasing in the level of regret. This technical finding underpins two results. First, regret bias potentially benefits the supplier when the profit margin of the supply chain is low. Under this condition, which, for example, would be the case for grocery goods, the retailer tends to under stock. In response to this tendency, if the level of regret increases, the newsvendor increases her order quantity, in turn positively affecting the supplier's profit, everything else being equal. Conversely, this means that the retailer's automation can harm the supplier. Second, the retailer's automation can even result in a self-harm. In particular, the regret bias of the newsvendor can boost her own performance, because the supplier may reduce his wholesale price when she becomes more biased via two different mechanisms. For the first mechanism, the more biased newsvendor is more likely to reject the supplier's contract, squeezing the price range of the supplier, who is striving to secure the newsvendor's participation. In the second mechanism, even if the newsvendor's participation is secured, regret bias may cause her to choose an order quantity that is more sensitive to the wholesale price charged by the supplier. In this setting, as the newsvendor becomes more biased, the supplier has to offer a more favorable wholesale price, to encourage the newsvendor to order.

The remainder of this study proceeds as follows. In Section 2, we review the related literature. In Section 3, we describe our model and incorporate regret in a centralized setting. In Section 4, we present and analyze the model in a decentralized setting. In Section 5, we examine the impact of regret on the equilibrium order quantity and supply chain profit and show that regret bias can induce system coordination under the right conditions. In Section 6, we investigate the impact of regret on the supplier's equilibrium wholesale price and profit. In Section 7, we investigate the impact of regret on the newsvendor's profit. In Section 8, we study which supply chain members win or lose from automation. Section 9 concludes the paper.

2. Literature Review

This study contributes to the rich literature on regret bias. Bell (1982, 1983) first incorporates regret into the utility function and shows that it can explain certain well-known behavioral anomalies. Nasiry and Popescu (2012) and Özer and Zheng (2016) have recognized that regret can explain consumers' purchase behavior. The literature has also recognized that regret can explain the manager's decision. Schweitzer and Cachon (2000) posit that newsvendors attempt to minimize regret in their order decisions, thereby explaining newsvendor behaviors. Li and Liu (2021) utilize regret to explain the seller's dynamic pricing behavior. We complement this literature by using regret to explain newsvendor's managerial decision in a supply chain setting. We accordingly investigate the theoretical impact of managerial regret on the performance of supply chain members and the value of order automation.

There is also a rich literature that studies supply chains, where a retailer purchases the product from her supplier, then sells to consumers (Cachon 2003, Lariviere and Porteus 2001, Li and Petruzzi 2017). This literature stream examines the effects of downstream retailer parameters, such as uncertainty or pricing power on the upstream supplier at equilibrium. This stream often models supply chains under the assumption that retailers are unbiased decision makers, which is not necessarily the case in practice according to the behavioral literature above. We extend this literature by incorporating regret as a cognitive bias to investigate its theoretical impact in a classical selling-to-newsvendor framework (Lariviere and Porteus 2001). We thereby make four key contributions.

First, we find that regret is a cognitive bias that potentially benefits supply chains that must distribute their products for their business in a decentralized manner, even though that bias would never benefit the supply chains without a decentralized structure. Indeed, regret is a bias that could even coordinate a decentralized supply chain with its system-wide first-best benchmark. Second, we show that the regret bias of the newsvendor may benefit her supplier: The newsvendor's regret can be taken advantage of by the supplier and eventually come across as a surplus of the supplier, depending on the profit margin of the supply chain and the bias level of the newsvendor. Third, contrary to the literature that suggests that retailer bias should result in self-harm (Li 2019, Li et al. 2016), we find if the newsvendor forces her supplier to charge a lower wholesale price, and if the benefit from such a reduced wholesale price outweighs the mismatch costs caused by regret bias, then overall regret bias would benefit, rather than hurt the newsvendor, per se. Fourth, we illustrate that automation aiming to eliminate regret bias of the retailer can even result in a *lose-lose* situation for both the supplier and the retailer.

Overall, this study contributes to the general realm of AI, Industry 4.0, or big data in operations management (Choi et al. 2018, Cohen 2018, Kumar et al. 2018, Olsen and Tomlin 2020). Since AI introduces an interaction between human and technology, this study is particularly related to the human–machine interaction literature. For example, Dietvorst et al. (2015) find that in general humans are averse to forecasts made by an algorithm, even when they outperform their less accurate human counterparts. Dietvorst et al. (2018) further find that algorithmic aversion can be reduced when individuals have the ability to manipulate and make adjustments to the algorithm. Cui et al. (2021) have recently conducted field experiments, and documented that the supplier factors in the retailers' adoption of automation when making pricing decisions. Consequently, the supplier would charge different wholesale prices to retailers with different levels of automation. We follow suit to study the impact of retailer's adoption of automation and show that AI automation can lead to a better or worse performance for the decentralized supply chain.

3. The Regretful Retailer

In this section, we introduce regret to the classic newsvendor problem. In the algorithmic newsvendor problem, a decision maker decides an order quantity before observing the realization of random demand D. Given a unit cost c (≥ 0) and a unit price p ($\geq c$), the order quantity q^* that maximizes the expected profit $p\mathbb{E}[D \wedge q] - cq$, where $\mathbb{E}[\cdot]$ is the expectation operator and $x \wedge y = \min\{x, y\}$, is characterized by $F(q^*) = \beta$, where $F(\cdot)$ is the distribution function of D and $\beta \equiv (p - c)/p$ is the critical fractile. Note that the critical fractile β is equal to the ratio of the underage cost $p - c$ and p, the sum of the underage cost $p - c$ and overage cost c. Thus, an unbiased automatic order quantity is $q^* = F^{-1}(\beta)$, and its correspondingly expected profit is $\pi^* = p\mathbb{E}[D \wedge q^*] - cq^*$.

Within this construct, a regretful newsvendor exhibits cognitive bias in caring "about reducing ex-post inventory error, the deviation between the order quantity and realized demand." In essence, "[t]his preference could develop from the decision maker's anticipated regret or disappointment from not choosing the ex-post optimal order quantity (realized demand), even though that order quantity is rarely the ex-ante optimal order quantity" (Schweitzer and Cachon 2000). Thus, the biased newsvendor places an order *as though* it maximizes

$$p\mathbb{E}[D \wedge q] - cq - \gamma\mathbb{E}[|q - D|], \tag{1}$$

where $\gamma \geq 0$, rather than the expected profit $p\mathbb{E}[D \wedge q] - cq$. In other words, a regretful newsvendor *behaves* as though it were maximizing (1) in lieu of maximizing $pE[D \wedge q] - cq$. From the perspective of newsvendor trade-off between underage and overage, regret causes an extra cognitive underage cost γ when the realized demand is higher than the order quantity ($D > q$) and an extra (and equal size of) cognitive overage cost γ when the realized demand is lower than the order quantity ($D \leq q$). As a result, the biased newsvendor behaves as though the underage cost is $p - c + \gamma$ (rather than $p - c$), whereas the overage cost is $c + \gamma$ (rather than c).

In (1), the parameter γ is the degree to which missing demand induces regret, thus can be interpreted as the regret level. If $\gamma > 0$, a newsvendor is subjected to the regret bias. The higher of the value γ, the more biased the newsvendor. Moreover, $\gamma = 0$ denotes a newsvendor that is not at all biased, and the newsvendor behaves as the classic newsvendor solution prescribes. To contrast against the regret bias we refer to a newsvendor defined by $\gamma = 0$ as an *unbiased automatic* newsvendor.

The newsvendor's regret or disappointment $\gamma|q - D|$ is defined as linear in the ex-post inventory error $|q - D|$ to reflex regret increases in the magnitude of the ex-post inventory error, and there is no regret when ex-post inventory error is absent (Schweitzer and Cachon 2000). This particular linear function allows us to capture the phenomenon of newsvendor regret without obfuscating our theoretical analysis; it also has been analytically studied and empirically validated in different settings (Engelbrecht-Wiggans and Katok 2008, Filiz-Ozbay and Ozbay 2007). In the context of newsvendor experiments, Bostian et al. (2008) test different forms for the regret function and find that the linear regret fits their experimental data. Particularly, after examining integer powers of the inventory error $|q - D|$ from one to five, they find that the linear model in (1) performs better (or at least not worse) than models of higher powers.

Lemma 1.

a. *A newsvendor described by regret parameter* γ *orders a quantity* $\hat{q}(\gamma)$ *such that* $F(\hat{q}(\gamma)) = \hat{\beta}(\gamma)$, *where* $\hat{\beta}(\gamma) \equiv (p - c + \gamma)/(p + 2\gamma)$. *Hence, the order quantity increases in* γ, *that is,* $\hat{q}'(\gamma) > 0$ *if and only if* $\beta < 1/2$.
b. *Accordingly, the newsvendor's expected profit* $\hat{\pi}(\gamma)$ *is decreasing*[1] *in the regret parameter* γ, *that is,* $\hat{\pi}'(\gamma) \leq 0$. *Consequently, automation always improves the retailer's profit, that is,* $\hat{\pi}(\gamma) \leq \hat{\pi}(\gamma = 0) = \pi^*$.

Lemma 1a indicates that, as in the classical newsvendor problem, the biased newsvendor's optimal order quantity can also be explained by the underage and overage costs. That is, a biased newsvendor's optimal order quantity is characterized by the ratio of the biased newsvendor's underage cost $p - c + \gamma$ and $p + 2\gamma$ (the summation of biased underage cost $p - c + \gamma$ and biased overage cost $c + \gamma$). To contrast against the regret bias, we therefore refer to β as *unbiased* fractile, while $\hat{\beta}(\gamma)$ as *biased* fractile. In this perspective, the critical fractile caused by regret bias alone is $\frac{\gamma}{\gamma+\gamma} = 1/2$, because by definition the regret causes the same amount of unit cognitive disutility (γ) for overage and underage. The relationship between the critical fractile caused by regret bias (1/2) and the unbiased fractile β determines whether the biased newsvendor's order quantity is decreasing or increasing in the bias level γ. Consequently, regret bias creates a pull-to-center effect. In particular, if $\beta > 1/2$, then the critical fractile decreases as the regret bias becomes stronger, which leads to a smaller optimal ordering quantity; on the other hand, if $\beta < 1/2$, a stronger regret bias will result in a larger optimal ordering quantity. This behavior implies that regret can result in either an increase or a decrease in a newsvendor's service level, as defined by the no-stockout probability $F(\hat{q}(\gamma))$. In particular, if $\beta < 1/2$, then the service level increases with respect to γ; if $\beta > 1/2$, then the service level decreases with respect to γ. Note that this comparison between the regret induced fractile $1/2$ and the unbiased fractile β is useful for the forthcoming results.

Moreover, Lemma 1b indicates that a newsvendor's expected profit decreases in its regret parameter γ. Thus, regret is a bias that hurts the newsvendor, and the larger the bias, the larger the hit to the newsvendor's bottom line. AI automation can largely remove the human involvement in the decision process to reduce the impact of behavioral bias. Therefore, automation always benefits the newsvendor. We next show that automation can be a negative force in a decentralized supply chain.

4. Regret in a Supply Chain

We introduce our notion of selling-to-newsvendor pioneered by Lariviere and Porteus (2001). Consider a supply chain in which a supplier manufactures a single product that it sells to a newsvendor retailer that sells it to end consumers during a single period. The supplier produces the product at a unit production cost c and the retailer sells the product at a unit retail price p. The supplier first decides the unit wholesale price w it charges the retailer, whereas, for a given wholesale price w, the newsvendor retailer makes her order decision q to maximize her profit $p\mathbb{E}[q \wedge D] - wq$. A key observation for this setting is that the newsvendor accepts the supplier's contract if and only if $w \leq p$, where accepting the contract is profitable for the newsvendor. Moreover, the order quantity is $q = \bar{F}^{-1}(w/p)$, where $\bar{F}(\cdot) = 1 - F(\cdot)$. As a result, the imputed profit of the supplier is $(w - c)q = (w - c)\bar{F}^{-1}(w/p)$. Because there is a one-to-one mapping from $w \in [c, p]$ to $q \in [0, \bar{F}^{-1}(c/p)]$, the supplier's problem reduces to $\sup_{q \in [0, \bar{F}^{-1}(c/p)]} (p\bar{F}(q) - c)q$. From this perspective, q is a proxy for the supplier's wholesale price decision. Given this, the equilibrium order quantity is unique when $F(\cdot)$ is increasing generalized failure rate (IGFR), that is, the generalized failure rate of D, $g_D(x) := xf(x)/\bar{F}(x)$, is an increasing function, where $f(\cdot)$ is the density function of D. We thus assume that D is IGFR, which includes many commonly applied demand distributions, such as normal, lognormal, uniform, exponential, Weibull, gamma, and power. In summary, in this classical setting, the newsvendor *always* accepts the supplier's wholesale price contract as long as the wholesale price is less than the retail price. As a result, the supplier always has feasible wholesale prices to ensure a non-negative profit.

We now incorporate the notion of regret bias (Section 3) into this classical selling-to-newsvendor model. Recall that regret is a cognitive bias in which the newsvendor behaves as though considering ex-post inventory regret. Thus, the retailer's newsvendor problem boils down to the equivalent of (1) except with w in place of c. Consequently, the supplier's problem is

$$\begin{aligned} &\sup_{w \geq c} \ (w-c)q && \text{(OBJ)} \\ &\text{s.t. } q = \arg\max_q \ p\mathbb{E}[D \wedge q] - wq - \gamma\mathbb{E}[|q-D|] && \text{(IC)} \\ &\quad p\mathbb{E}[D \wedge q] - wq - \gamma\mathbb{E}[|q-D|] \geq 0. && \text{(IR)} \end{aligned} \tag{2}$$

The first constraint (IC) in Equation (2) ensures that the newsvendor behaves as though to optimally choose an order quantity q. The second constraint (IR) above ensures that the newsvendor accepts the contract because, by doing so, she behaves as though earning no less than her reservation which, without loss of generality, is normalized to zero. For the objective function (OBJ) in Equation (2), we note that the supplier, unlike the newsvendor, has no regret bias because the supplier does not hold inventory and has no ex-post inventory error. Also, Katok and Wu (2009) find that when human suppliers in a wholesale contract are matched with human newsvendors placing orders, suppliers quickly learn to set wholesale prices optimally. Thus, in Equation (2), the supplier is assumed to be sophisticated in the sense that he is not only a profit-maximizer but also can foresee the newsvendor's regret bias.

Given (2) Lemma 2 characterizes the newsvendor's order decision when the supplier offers her a wholesale price w.

LEMMA 2. (newsvendor response). *Define* $\bar{w}(\gamma) \equiv \bar{F}(\underline{q}(\gamma))(p+2\gamma) - \gamma$, *where* $\underline{q}(\gamma)$ *is the unique solution of* $\int_0^{\underline{q}(\gamma)} xf(x)dx = \gamma\mu/(p+2\gamma)$ *for* $\mu = \mathbb{E}[D]$.

a. *If the supplier's wholesale price contract is such that* $w \leq \bar{w}(\gamma)$, *then the order quantity of the newsvendor with regret parameter* γ *is* $\hat{q}_d(\gamma, w) = \bar{F}^{-1}(\frac{w+\gamma}{p+2\gamma})$. *Moreover, the order quantity decreases in the wholesale price:*

$$\frac{\partial \hat{q}_d(\gamma, w)}{\partial w} = -\frac{1}{(p+2\gamma)f(\hat{q}_d(\gamma))} < 0. \tag{3}$$

However, when $w > \bar{w}(\gamma)$, *the newsvendor rejects the supplier's contract.*

b. *The above* $\bar{w}(\gamma)$ *satisfies* $\bar{w}(\gamma) \leq p$. *Moreover,* $\bar{w}(\gamma)$ *decreases in the regret parameter* γ, *that is,* $\bar{w}'(\gamma) \leq 0$.

Lemma 2a shows that, as in the classic selling-to-newsvendor setting, there also exists a threshold value of wholesale price $\bar{w}(\gamma)$ above which the newsvendor declines the contract of the supplier. In particular, if the supplier offers a contract with a relatively generous wholesale price ($w \leq \bar{w}(\gamma)$), the newsvendor accepts the contract and places a positive order quantity. Moreover, in (3), $\frac{\partial \hat{q}_d(\gamma, w)}{\partial w} < 0$ means that the newsvendor orders less as the wholesale price goes higher. The magnitude of decreasing order due to the increasing wholesale price, that is, $|\frac{\partial \hat{q}_d(\gamma, w)}{\partial w}|$, depends on γ. As an example, for the uniform demand with a constant $f(\cdot)$, $|\frac{\partial \hat{q}_d(\gamma, w)}{\partial w}|$ always decreases in γ. That is, as the newsvendor becomes more biased, her order quantity becomes less sensitive to the wholesale price. However, if the wholesale price is relatively high ($w > \bar{w}(\gamma)$), the newsvendor declines the supplier's contract and does not order at all.

Lemma 2b further shows that $\bar{w}(\gamma)$ is less than p which is the unbaised newsvendor's threshold value, that is, $\bar{w}(\gamma) \leq p$. This means that even if the supplier charges an acceptable wholesale price (for the unbiased newsvendor), the biased newsvendor may not order if $w > \bar{w}(\gamma)$. In other words, the biased newsvendor considering the ex-post inventory error may not order even if doing so is profitable. This is indeed the case in laboratory studies simulating the newsvendor decision in Lariviere and Porteus (2001) setting. For example, in their controlled laboratory experiment where the newsvendors have the option to reject the contracts from their suppliers, Davis et al. (2014) find that newsvendors reject significantly more than the theory predicted and even do not accept contracts which are profitable for the unbiased newsvendor. Actually, Lemma 2b also indicates that the threshold value $\bar{w}(\gamma)$ decreases in the regret level, meaning that the more biased newsvendor is more likely to reject the supplier's contract, everything else being equal.

LEMMA 3. (supplier problem).

a. *There exists a unique* $\bar{\gamma}$ *such that the supplier's problem* (2) *has feasible solutions only when* $\gamma \leq \bar{\gamma}$. *Moreover,* $\bar{\gamma}$ *is characterized by* $F(\underline{q}(\bar{\gamma})) = (p-c+\bar{\gamma})/(p+2\bar{\gamma})$, *where* $\underline{q}(\cdot)$ *is defined in Lemma* 2.
b. *The supplier's problem in* (2) *can be reformulated as*

$$\begin{aligned} \pi_S(\gamma) := \max_q \ &\left[\bar{F}(q)(p+2\gamma) - \gamma - c\right]q \\ s.t. \quad &\underline{q}(\gamma) \leq q \leq F^{-1}(\hat{\beta}(\gamma)). \end{aligned} \tag{4}$$

Lemma 3a shows that the supplier has a feasible solution only when the regret parameter is relatively small ($\gamma \leq \bar{\gamma}$), because if the newsvendor's bias level is higher than $\bar{\gamma}$, the newsvendor never accepts the supplier's contract regardless of his decision for wholesale price. This is in contrast to the traditional selling-to-newsvendor model, where recall that feasible wholesale price solutions always exist. Moreover, the supplier's problem can be reformulated as a problem with a proxy variable q shown in Equation (4). We next solve (4) and explore the results and implications for the decentralized supply chain in the following sections.

5. The Supply Chain Profit

In this section, we study the solution to (4) to assess the overall impact of regret bias in the decentralized supply chain. We characterize the equilibrium outcomes as functions of the regret level by establishing that the supplier's optimal proxy q exists and is unique for any given regret level γ. Then, given those equilibrium outcomes, we illustrate that in contrast to the centralized analog in Section 3 the total expected profit for the decentralized system, as a whole, is not necessarily monotone decreasing in γ.

We begin by characterizing the optimal solution to (4) for any given regret parameter γ.

Proposition 1. (equilibrium order). *For any given regret parameter γ, the optimal solution to (4) exists and is unique. In particular, the optimal solution is*

$$\hat{q}_d(\gamma) = \begin{cases} \underline{q}(\gamma), & \text{if } \hat{\beta}(\gamma) \le G(\underline{q}(\gamma)) \quad (\text{Binding Equilibrium: BE}) \\ G^{-1}(\hat{\beta}(\gamma)), & \text{if } \hat{\beta}(\gamma) > G(\underline{q}(\gamma)) \quad (\text{Non-Binding Equilibrium: NBE}), \end{cases} \tag{5}$$

where $G(q) \equiv F(q) + qf(q)$.

Notice from Proposition 1 that, like in the case of the centralized setting, the order quantity in the decentralized supply chain also depends on the biased fractile $\hat{\beta}(\gamma)$. Specifically, Proposition 1 indicates that if the biased system fractile is relatively low such that $\hat{\beta}(\gamma) \le G(\underline{q}(\gamma))$, then $\hat{q}_d(\gamma) = \underline{q}(\gamma)$. In such a case, the supplier offers the wholesale price $\bar{w}(\gamma)$ so that the biased newsvendor considering ex-post inventory error accepts the contract offered by the supplier but anticipates the minimal surplus. In other words, the supplier will be in a position to set his wholesale price to the point where the newsvendor would not accept the contract for a higher wholesale price. This equilibrium where the (IR) constraint in Equation (2) is binding, we term *binding equilibrium* (BE).

However, if the biased system fractile is relatively high such that $\hat{\beta}(\gamma) > G(\underline{q}(\gamma))$, the (IR) constraint in Equation (2) is not binding, that is, the automatic newsvendor anticipates to earn more than the minimal surplus. We term this equilibrium *non-binding equilibrium* (NBE). Note that, for the automatic newsvendor where $\underline{q}(\gamma = 0) = 0$, $\hat{\beta}(\gamma = 0) = \beta > G(\underline{q}(\gamma = 0)) = 0$ always holds. That is, NBE is the only equilibrium type for the supply chain with an automatic newsvendor; it is the newsvendor's bias leading to a new equilibrium type, namely BE. In fact, as the newsvendor becomes more biased (i.e., the regret parameter γ increases), it is more likely to have the BE.

Proposition 2. (order quantity and regret).

a. *The equilibrium order $\hat{q}_d(\gamma)$ in NBE increases in the regret parameter γ, that is, $\hat{q}'_d(\gamma) \ge 0$, if and only if $\beta \le 1/2$.*
b. *However, $\hat{q}'_d(\gamma) \ge 0$ always holds in BE.*

Proposition 2a shows that, in NBE, the impact of regret bias in the decentralized setting is similar to its impact in the centralized setting in the sense that the distortion from regret is such that the equilibrium order quantity increases (resp. decreases) with respect to the regret parameter if and only if the supply chain's unbiased fractile β is lower (resp. higher) than the regret fractile 1/2. In a decentralized setting, the pull-to-center effect can prevail as in the centralized setting.

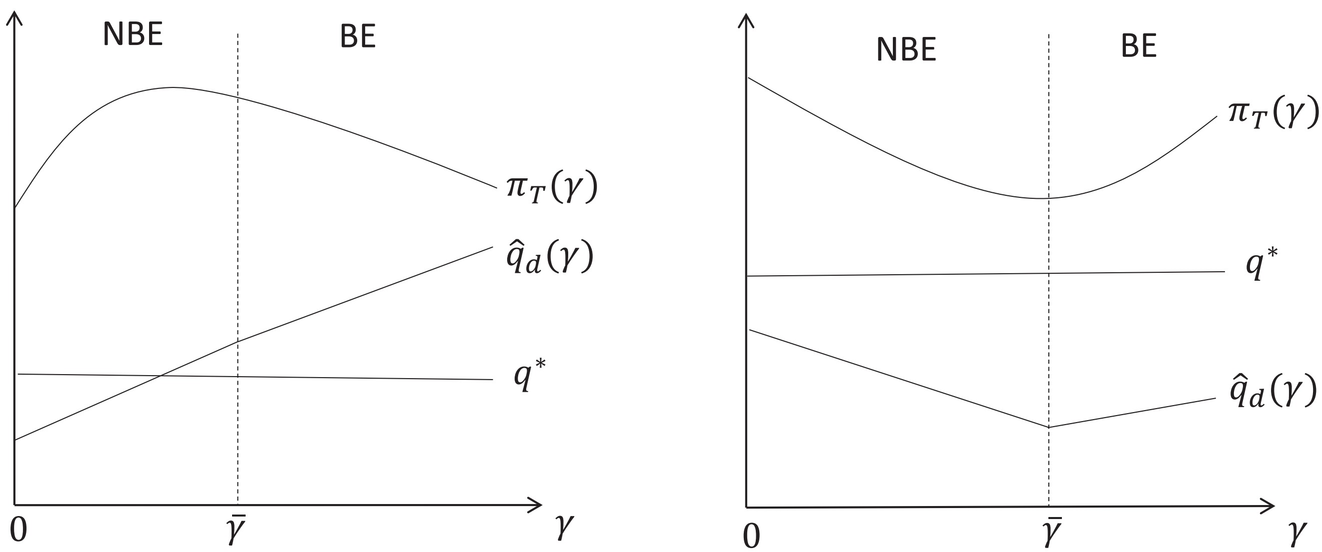
Proposition 2b shows that in BE the equilibrium order quantity always increases in the regret bias γ regardless of the value of profit margins. Intuitively, under the case of BE, the newsvendor achieves the minimal surplus, and she serves only as a distributor for the supplier's product. Under this case, when the newsvendor becomes more biased, her expected utility decreases, and the supplier has to reduce the wholesale price to secure the newsvendor's participation. As a result, the newsvendor orders more as she becomes more regretful.

Although Proposition 2a is qualitatively similar to Lemma 1a in that it characterizes a behavioral pull-to-center effect arising from regret bias, the implication of decision bias in a decentralized supply chain can be different from the centralized system. In particular, we note that when the newsvendor anticipates a surplus higher than the minimal surplus, $\hat{q}_d(\gamma)$ increases in γ when $\beta \le 1/2$. This means that, *ceteris paribus*, a biased newsvendor is more prone to overorder than if it were unbiased. This becomes more evident for the BE case in Proposition 2b, where the newsvendor anticipates the minimal surplus. For such a case, regret bias always leads to a larger order quantity. This is interesting because supply chain decentralization is a force that drives the newsvendor to order less; while regret, a cognitive bias, serves as a counter force.

To develop insight into the net effect of these two forces, we investigate the impact of regret bias on the expected profit of the supply chain:

$$\pi_T(\gamma) \equiv p\mathbb{E}[D \wedge \hat{q}_d(\gamma)] - c\hat{q}_d(\gamma). \tag{6}$$

Figure 1 An illustration of Proposition 3 and Lemma 4 Using a Uniform Demand



(a) $\beta \leq 1/2$ (b) $\beta > 1/2$

Recall from Lemma 1 that regret is a bias that necessarily robs from a newsvendor's bottom line in a centralized setting. As Proposition 3 illustrates this may not be true in the analog setting in which the newsvendor purchases from her supplier.

Proposition 3. (supply chain profit). *Suppose $\beta > 1/2$. The supply chain's expected profit $\pi_T(\gamma)$ is decreasing in γ in NBE. However, $\pi_T(\gamma)$ is increasing in γ in BE.*

Proposition 3 illustrates that the decentralized supply chain may benefit from the newsvendor's regret bias. For a relatively high unbiased fractile ($\beta > 1/2$), although NBE is sufficient to guarantee that regret will translate into a lower total expected profit for the decentralized supply chain, just as it does for the centralized supply chain, that guarantee is lost in the case of BE.

For insights, consider the following hypothetical construct. Suppose an unbiased central planner aims to determine the first-best order quantities to maximize the total expected profits of the supplier and the newsvendor. The expected profit of such a system is $p\mathbb{E}[D \wedge q] - cq$. Therefore, the first-best order quantity is defined by $F(q^*) = \beta$. The performance of decentralized supply chain depends on the relationship between their order quantities $\hat{q}_d(\gamma)$ and the system-wide first-best order quantity q^*. The closer $\hat{q}_d(\gamma)$ to q^*, the better the performance of the decentralized supply chain. Thus, we plot these two quantities and the equilibrium profit as functions of in γ using a uniform demand in Figure 1. In this figure, the equilibrium is binding (resp. non-binding) when regret level is relatively high (resp. low); see Appendix for details. By Figure 1, it can be clearly seen that when $\beta \leq 1/2$, the supply chain profit can decrease or increase in the level of regret.

Figure 1 shows that at one extreme q^* is greater than the equilibrium order quantity $\hat{q}_d(\gamma)$ that would result if the newsvendor were unbiased ($\gamma = 0$), but at the other extreme q^* could be either less or greater than $\hat{q}_d(\gamma)$, which would result if the newsvendor were extremely biased ($\gamma = \bar{\gamma}$).

Lemma 4.

a. *An (unbiased) centralized planner orders more than the unbiased decentralized supply chain. That is, $q^* > \hat{q}_d(\gamma = 0)$.*
b. *Suppose $\gamma = \bar{\gamma}$. An (unbiased) centralized planner orders less than the (biased) decentralized system if $\beta \leq 1/2$ but orders more than the (biased) decentralized system if $\beta > 1/2$. That is, $q^* < \hat{q}_d(\gamma = \bar{\gamma}) \Longleftrightarrow \beta \leq 1/2$.*

Lemma 4a essentially means that the unbiased newsvendor in a decentralized setting underorders compared to its centralized analog. This specific distinction between a decentralized supply chain and a centralized chain results in double marginalization, which is a manifestation of the independent objectives of the two firms within a decentralized chain and ultimately leads to a reduced level of production for the decentralized chain compared to its centralized analog, everything else being equal. Furthermore, Lemma 4b shows that the extremely biased newsvendor with a regret level $\bar{\gamma}$ in a decentralized setting may underorder or overorder compared to its centralized analog, depending on the value of (unbiased) fractile β. Perhaps the biased newsvendor in the decentralized system can order more than the unbiased newsvendor in the centralized system, particularly when $\beta \leq 1/2$.

This possibility begs the question whether regret bias could extract a balanced (i.e., symmetric) distortion of both the overage and underage costs that the central planner assesses so that the equilibrium order quantity corresponds to the first-best order decision. Proposition 4 investigates this possibility.

PROPOSITION 4. (coordination). *Suppose $\beta \leq 1/2$. Then, $\hat{q}_d(\gamma^*) = q^*$. In particular,*

$$\gamma^* = \begin{cases} \dfrac{p\int_0^{F^{-1}(\beta)} xf(x)dx}{\mu - 2\int_0^{F^{-1}(\beta)} xf(x)dx} & \text{if } \hat{\beta}(\gamma^*) \leq G(\underline{q}(\gamma^*)) \\ \dfrac{g_D(F^{-1}(\beta))c}{2(1-\beta)[1-g_D(F^{-1}(\beta))]-1} & \text{if } \hat{\beta}(\gamma^*) > G(\underline{q}(\gamma^*)). \end{cases} \tag{7}$$

Proposition 4 shows that regret bias can induce system coordination under the right conditions. If the profit margin is relatively low ($\beta \leq 1/2$), then there exists a level of regret at which the newsvendor would converge on the system-wide coordinating order quantities. Regret is a bias that potentially offsets the effect of decentralization so that a system actually is equivalent to its centralized benchmark.

Given the inherent trade-offs exemplified by Propositions 3–4, we dive deeper into the interplay between the supplier and the newsvendor retailer to ascertain who wins and who loses from regret bias in the decentralized supply chain by studying how regret affects each player separately in equilibrium.

6. The Supplier Profit

In this section, we examine the impact of regret bias on the supplier's expected profit $\pi_S(\gamma)$. To that end, we establish Proposition 5 to characterize how the equilibrium wholesale price $\hat{w}_d(\gamma)$ behaves as a function of the regret bias.

PROPOSITION 5. (wholesale price).

a. *In BE, the equilibrium wholesale price $\hat{w}_d(\gamma)$ always decreases in γ, that is, $\hat{w}_d'(\gamma) \leq 0$.*
b. *However, in NBE, $\hat{w}_d(\gamma)$ increases in γ when the biased fractile is relatively low, that is, $\hat{w}_d'(\gamma) \geq 0$ when $\hat{\beta}(\gamma) \leq \mathcal{B}$, where $\mathcal{B} \equiv 1/2 + F^{-1}(1/2)f(F^{-1}(1/2))$.*

Proposition 5 shows that the equilibrium wholesale price decreases or increases in the level of the regret bias depending on the case of the equilibrium. For the case of BE, the supplier sets a wholesale price to secure the newsvendor's participation. As the newsvendor becomes more biased, securing the newsvendor's participation becomes more challenging for the supplier, and his wholesale price becomes more lenient. For the NBE case, the supplier may raise his wholesale price as the newsvendor becomes more biased, because the newsvendor's order becomes less sensitive to the wholesale price as the newsvendor becomes more biased (Lemma 2). Consequently, the supplier's pricing power is enhanced. This is true especially when the biased fractile is relatively low, where the order quantity is already relatively low (Lemma 1). As an illustration, consider the setting with a uniform demand $D \sim U[0, 100]$, where $\mathcal{B} = 1$. For this setting, $\hat{\beta}(\gamma) < \mathcal{B}$ always holds. Then, $\hat{w}_d(\gamma)$ always increases in γ for the NBE case. The increasing pricing power can enhance the supplier's performance as shown in Proposition 6.

PROPOSITION 6. (supplier profit).

a. *For the NBE case, the supplier's profit $\pi_S(\gamma)$ increases in γ, that is, $\pi_S'(\gamma) \geq 0$ if and only if $\hat{\beta}(\gamma) \leq \mathcal{B}$, where $\mathcal{B}$ is defined in Proposition 5.*
b. *For the BE case, $\pi_S'(\gamma) \geq 0$ when $\gamma < \mathcal{L}$, where $\mathcal{L} \equiv p\int_0^{F^{-1}(1/2)} xf(x)dx / [\mu - 2\int_0^{F^{-1}(1/2)} xf(x)dx]$.*

The qualitative impact of regret on the supplier's equilibrium profit boils down to an unambiguous, but equilibrium-specific test. If the equilibrium is non-binding, as in Proposition 6a, then the supplier suffers from regret if the biased fractile is relatively high ($\hat{\beta}(\gamma) > \mathcal{B}$). In such a case, the qualitative effect on the supplier in the supply chain is analogous to that on the central planner, albeit for a different reason: whereas regret translates into decreased operational efficiency for the central planner, regret, in this case, translates into decreased order quantity from the retailer. If the system-biased fractile is relatively high, the newsvendor retailer in the decentralized system confronts a situation in which her safety stock should be positive (Lemma 1). Correspondingly, in such a situation if the retailer is biased, her order quantity will tend to decrease, which would negatively affect the supplier's profit, everything else being equal. Rather, in NBE case, if $\hat{\beta}(\gamma) > \mathcal{B}$ is not true, the supplier would not necessarily suffer from selling to a biased newsvendor. Intuitively, regret in this case translates into increased pricing power that the supplier can leverage to his advantage in the supply chain.

Perhaps of more interest, Proposition 6b indicates that the supplier can also benefit from regret in the BE case, where regret always results in a lower wholesale price (Proposition 5a). Intuitively, when the regret level of the newsvendor is relatively low, she stocks relatively low in the BE case. Thus, the newsvendor would stock more as she becomes more biased (Proposition 2b), benefiting the supplier. As an illustration of Proposition 6, consider again the setting of $D \sim U[0, 100]$. For this particular example, where $\mathcal{B} = 1$ and $\mathcal{L} = p/2$, the supplier benefits from regret bias in the NBE case because $\hat{\beta}(\gamma) < \mathcal{B}$. Similarly, the supplier would also benefit from regret in the BE case because $\gamma < \mathcal{L}$ always holds (see Appendix).

7. The Newsvendor Profit

Next we examine the impact of the regret bias on the newsvendor retailer's expected profit:

$$\begin{aligned}\pi_R(\gamma) &= p\mathbb{E}[D \wedge \hat{q}_d(\gamma)] - \hat{w}_d(\gamma)\hat{q}_d(\gamma) \\ &= p\mathbb{E}[D \wedge \hat{q}_d(\gamma)] - [(p+2\gamma)\bar{F}(\hat{q}_d(\gamma)) - \gamma]\hat{q}_d(\gamma) \\ &= p\int_0^{\hat{q}_d(\gamma)} xf(x)dx + \gamma\hat{q}_d(\gamma)[1 - 2\bar{F}(\hat{q}_d(\gamma))].\end{aligned} \quad (8)$$

Given (8), it is not immediately obvious how changes in γ affect $\pi_R(\gamma)$ because there are two drivers at play. One driver is the direct effect of γ on the retailer's equilibrium expected profit for a given wholesale price. The direct effect of regret bias is a negative force on the retailer's profit because the retailer makes a non-optimal ordering decision, everything else being equal. The second driver is an indirect effect of γ: the supplier may charge a different wholesale price when the level of newsvendor regret changes. The final impact of regret bias depends on the relative magnitudes of these two forces. Ultimately, the functional outcome of that trade-off is distribution dependent and complicated, but Proposition 7 provides one useful sufficiency test for assessing the impact of regret on $\pi_R(\gamma)$.

Proposition 7. (newsvendor profit).

a. *In the BE case, the newsvendor's profit $\pi_R(\gamma)$ increases in γ, that is, $\pi'_R(\gamma) \geq 0$ if $\gamma > \mathcal{L}$, where $\mathcal{L}$ is defined in Proposition 6.*
b. *In the NBE case, there always exist $\tilde{\beta}(\geq 0)$ and $\tilde{\gamma}(\geq 0)$ such that the newsvendor's profit $\pi_R(\gamma)$ increases in γ over a region of $\gamma \in [0, \tilde{\gamma}]$ when $\beta > \tilde{\beta}$.*

Proposition 7 shows that, given the existence of distributions that meet the Proposition 7 test, the newsvendor benefits from her own decision bias in a decentralized supply chain, although she is always hurt from the bias in the centralized system (Lemma 1). Intuitively speaking, as the newsvendor becomes more biased, although she is worse off for a given wholesale price, the supplier may charge a lower wholesale price. If the benefit from the reduced wholesale price outweighs the loss due to regret bias, regret as a cognitive bias may benefit the newsvendor altogether. This happens either in the BE case, when the newsvendor bias is relatively high ($\gamma > \mathcal{L}$), or in the NBE case, when the decision bias is relatively low ($\gamma < \tilde{\gamma}$). In BE, for a relatively high regret bias ($\gamma > \mathcal{L}$), the newsvendor is in a position with a relatively high order quantity (Proposition 2a). Consequently, a reduced wholesale price due to regret bias (Proposition 5a) adds a significant profit to the newsvendor. In the NBE case, the wholesale price is not necessarily decreasing as the newsvendor becomes more biased according to Proposition 5. Thus, the newsvendor bias results in self-benefit when the operational loss due to regret is relatively low, which occurs where the regret bias is relatively low.

Although Proposition 7 provides a useful logical taxonomy of the potential effects resulting from newsvendor bias on her own profit, the concern of applicability of Proposition 7 remains. To address this concern we consider a power distribution, a more generalized distribution than uniform.

Example 1. Consider a power distribution, that is, $f(x) = kx^{k-1}$, where $k \geq 0$ for $x \in [0,1]$. Then, $\bar{\gamma}$ is such that $(p - c + \bar{\gamma})^{1+k} = (p + 2\bar{\gamma})\bar{\gamma}^k$. Furthermore, the equilibrium is binding when $(p - c + \gamma)^{1+k} \leq (p + 2\gamma)\gamma^k(1 + k)^{1+k}$; otherwise, the equilibrium is non-binding. Moreover, for this particular demand, $\mathcal{L} = p/(2^{1+1/k} - 2)$ and $\mathcal{B} = (1 + k)/2$.

To illustrate Example 1, consider an instance of $k = 0.4$, $p = 1$ and $c = 0.1$. This is a case of high profit margin, which can be true for the products such as information goods. Then, $(p - c + \bar{\gamma})^{1+k} = (p + 2\bar{\gamma})\bar{\gamma}^k \Longleftrightarrow \bar{\gamma} = 0.58$ and $(p - c + \gamma)^{1+k} \leq (p + 2\gamma)\gamma^k(1 + k)^{1+k} \Longleftrightarrow \gamma \geq 0.19$. Example 1 therefore implies that the equilibrium is non-binding when γ is relatively low ($\gamma < 0.19$), whereas, the equilibrium is binding when γ is relatively high ($0.19 \leq \gamma \leq 0.58$). In the BE case, Proposition 7a implies that $\pi'_R(\gamma) \geq 0$ always holds for this example because $\mathcal{L} = 0.1 < 0.19$. In the NBE case, Proposition 7b indicates that newsvendor regret can result in a self-beneficial situation because $\hat{\beta}(\gamma) < \mathcal{B} \Longleftrightarrow \gamma < 0.5$ always holds, where $\mathcal{B} = 0.7$, and $\gamma < 0.19$ in NBE. Overall, this example illustrates that regret bias of the newsvendor can boost her self-performance in both the case of BE and the case of NBE.

Figure 2 The Supplier's Profit $\pi_S(\gamma)$ and the Newsvendor's Profit $\pi_R(\gamma)$ when $f(x) = kx^{k-1}$, where $k = 0.4$, $c = 0.1$, and $p = 1$ [Color figure can be viewed at wileyonlinelibrary.com]

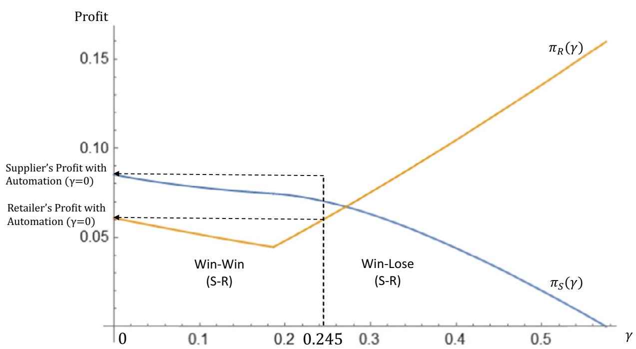
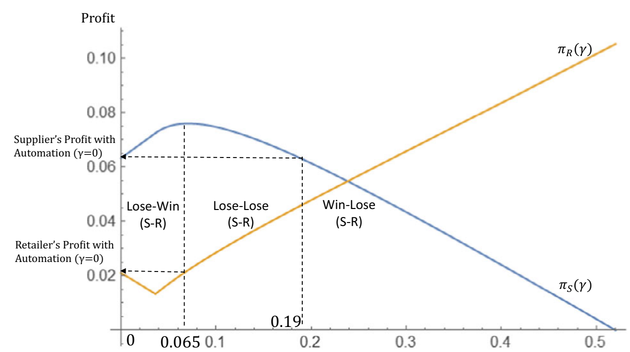


Figure 3 The Supplier's Profit $\pi_S(\gamma)$ and the Newsvendor's Profit $\pi_R(\gamma)$ when $f(x) = kx^{k-1}$, where $k = 2$, $c = 0.7$, and $p = 1$ [Color figure can be viewed at wileyonlinelibrary.com]



8. Who Loses and Who Wins from Automation?

To synthesize the results of Sections 6 and 7, we characterize and classify the interplay between the supplier and the retailer by summarizing who wins and who loses (and when) from automation aiming to eliminate regret bias in the decentralized supply chain. Given the observations from Section 4 on the decentralized supply chain overall, we are particularly interested in identifying circumstances when a win-win outcome is possible and, somewhat more perversely, whether or not circumstances exist when a lose-lose outcome would prevail. Based on the results characterized by Propositions 6–7, then, there are, in principle, four possible macro-level outcomes (lose-lose, lose-win, win-lose, and win-win for the supplier and the newsvendor, respectively), depending on the shapes of $\pi_S(\gamma)$ and $\pi_R(\gamma)$ as a function of γ. We illustrate these outcomes by specifying a power demand distribution.

If a given power distribution and system fractile are such that $\pi_S(\gamma)$ is monotone (decreasing) in γ while $\pi_R(\gamma)$ is non-monotone (decreasing–increasing) in γ, automation would result in either a win-win situation that both firms benefits from automation, or in a win-lose situation in that the supplier benefits from the retailer's automation, but she does so at the retailer's expense. As Figure 2 alludes, the case of a power distribution, used to illustrate Example 1, defines one example in which these possible outcomes prevail. In particular, automation can result in a win-win (win-lose) situation when regret bias is relatively low (high). In this case, if the newsvendor's regret level is already low ($\gamma < 0.245$), both firms benefit from automation; however, if the regret level is comparatively higher, the supplier benefits from automation but at the expense of the retailer.

If the power distribution and system fractile are such that both $\pi_S(\gamma)$ and $\pi_R(\gamma)$ are non-monotone as in Figure 3, then a lose-lose situation is also possible. In particular, in this case, if the regret level is relatively moderate ($0.065 < \gamma < 0.19$), both the retailer and the supplier ironically end up worse off as a result of automation. We attribute this overall shrinking pie to the increased deleterious system-wide effects stemming from the double marginalization effects. This reduction is produced by the supplier's exertion of his increased monopoly pricing power in response to the newsvendor's automation. The end result in this case is akin to a lose-lose outcome.

9. Concluding Remarks

In this study we investigate the implications and applications of ordering automation in a supply chain. In a classical selling-to-newsvendor framework, we characterize the supplier's and the newsvendor's optimal decisions in equilibrium, and show that their expected profits in equilibrium can decrease or increase with the level of regret, depending on the specific demand distribution and the value of the system-wide critical fractile. We find that ordering automation potentially can be a negative force in a decentralized supply chain. In showing these results, we find that two different types of equilibria exist, namely the binding equilibrium and the non-binding equilibrium, where automation can be self-harmful. We attribute these results to the interplay of competing forces by which human behavior (particularly, regret) yields a biased decision that disfavors the newsvendor, on the one hand, but provides a decreased wholesale price that favors the newsvendor, on the other.

From an operations perspective, AI introduces an interaction between humans and technology, and would have a significant impact on operations and supply chain processes. Our result implies that automation aiming to eliminate regret can actually hurt, rather than benefit each supply chain member depending on the retailer's existing regret level. In the most perverse of these potential situations, a lose-lose outcome prevails in which automation can potentially leave both the retailer and supplier worse off in equilibrium. Our results may have value for firms adopting AI automation tied to reducing retailer's order bias. Since AI automation presumably can be initiated by suppliers or by newsvendors, our results suggest the following strategic considerations for settings characterized by uncoordinated or unilateral bias AI automation opportunities. If regret bias is low (high), the supplier (newsvendor) should resist relinquishing unilateral control of AI automation efforts to the newsvendor (supplier); but, if regret bias is moderate, the supplier (retailer) should help facilitate retailer-led (supplier-led) AI automation initiatives.

In this paper, we model the adoption of AI as a removal of the retailer's decision bias. Clearly, there are many other factors to be considered for adopting AI. For example, the benefits of AI include reducing labor cost and improving efficiency whereas the drawbacks of AI include lack of flexibility and potential ethical issues. The retailer should consider all these potential benefits and drawbacks when deciding whether to implement it. As AI becomes more advanced and smarter, the trade-off also becomes more challenging.

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Appendix A. Proofs

Proof of Lemma 1.

a. From (1), the biased newsvendor's problem is

$$\max_q \Pi(q) = p\int_0^q f(x)xdx + pq\bar{F}(q) -\gamma\int_0^q (q-x)f(x)dx - \gamma\int_q^\infty (x-q)f(x)dx - cq, \quad \text{(A1)}$$

where $f(\cdot)$ is the density function of D. The first-order condition is $\Pi'(q) = pf(q)q - pqf(q) + p\bar{F}(q) -\gamma\int_0^q f(x)dx + \gamma\int_q^\infty f(x)dx - c = (p+2\gamma)\bar{F}(q) - \gamma - c$. Consequently, $\Pi''(q) = -(p+2\gamma)f(q) < 0$, which implies that $\Pi(q)$ is concave in q. Thus, the newsvendor with a regret level γ orders a quantity $\hat{q}(\gamma)$ satisfying the first-order condition, that is, $\bar{F}(\hat{q}(\gamma)) = \frac{c+\gamma}{p+2\gamma}$. Moreover, taking the derivative of γ on both sides of $\bar{F}(\hat{q}(\gamma)) = \frac{c+\gamma}{p+2\gamma}$, we have $-f(\hat{q}(\gamma))\hat{q}'(\gamma) = \frac{p+2\gamma-2(c+\gamma)}{(p+2\gamma)^2} = \frac{p-2c}{(p+2\gamma)^2} = \frac{p(2\beta-1)}{(p+2\gamma)^2}$. Thus, $\hat{q}'(\gamma) > 0 \iff \beta < 1/2$.

b. With the order quantity $\hat{q}(\gamma)$, the newsvendor's resulting expected profit is $\hat{\pi}(\gamma) \equiv \pi(\hat{q}(\gamma)) = p\mathbb{E}[D\wedge\hat{q}(\gamma)] - c\hat{q}(\gamma)$. As a result, $\hat{\pi}'(\gamma) = [p\bar{F}(\hat{q}(\gamma)) - c]\hat{q}'(\gamma) = \frac{\gamma(p-2c)}{p+2\gamma}\hat{q}'(\gamma) = \frac{\gamma p(2\beta-1)}{p+2\gamma}\hat{q}'(\gamma)$, where the second equality is from $\bar{F}(\hat{q}(\gamma)) = \frac{c+\gamma}{p+2\gamma}$. Thus, $\beta > 1/2 \Longrightarrow \hat{\pi}'(\gamma) < 0$ because $\hat{q}'(\gamma) < 0$ and $2\beta-1 > 0$. However, $\beta < 1/2 \Longrightarrow \hat{\pi}'(\gamma) < 0$ because $\hat{q}'(\gamma) > 0$ and $2\beta-1 < 0$.

Proof of Lemma 2.

a. With the biased order quantity $q = \bar{F}^{-1}(\frac{w+\gamma}{p+2\gamma})$, the newsvendor's objective function in Equation (A1) becomes

$$\Pi(q)|_{q=\bar{F}^{-1}(\frac{w+\gamma}{p+2\gamma})} = p\int_0^q f(x)xdx + pq\bar{F}(q) - \gamma\int_0^q (q-x)f(x)dx - \gamma\int_q^\infty (x-q)f(x)dx - wq = (p+2\gamma)\int_0^q xf(x)dx - \gamma\mu,$$

which increases in q. As a result, when $q = \bar{F}^{-1}(\frac{w+\gamma}{p+2\gamma})$, $\Pi(q) \geq 0$ means that $\bar{F}^{-1}(\frac{w+\gamma}{p+2\gamma}) \geq \underline{q}(\gamma)$, where $\underline{q}(\gamma)$ is defined by $\int_0^{\underline{q}(\gamma)} xf(x)dx = \frac{\gamma\mu}{p+2\gamma}$. Consequently, when $q = \bar{F}^{-1}(\frac{w+\gamma}{p+2\gamma})$, $\Pi(q) \geq 0 \iff w \leq \bar{w}(\gamma)$. Thus, when the wholesale price is relatively low ($w \leq \bar{w}(\gamma)$), the newsvendor accepts the wholesale price contract with the equilibrium order quantity $\hat{q}_d(\gamma, w) = \bar{F}^{-1}(\frac{w+\gamma}{p+2\gamma})$. Taking derivation of $\hat{q}_d(\gamma, w)$ with respective of w, we have (3). Moreover, when the wholesale price is relative high ($w > \bar{w}(\gamma)$), the newsvendor declines the wholesale price contract.

b. Suppose that $p < \bar{w}(\gamma)$. Then, from (a), the newsvendor's profit $\Pi(\hat{q}_d(\gamma, w)) \geq 0$ when $w = p$. However, $\Pi(\hat{q}_d(\gamma, p)) = p\mathbb{E}[D\wedge q] - pq - \gamma\mathbb{E}[|q-D|]|_{q=\hat{q}_d(\gamma,p)} < 0$, which contradicts to $\Pi(\hat{q}_d(\gamma, w)) \geq 0$. Thus, $\bar{w}(\gamma) \leq p$.

We take the derivative of the left-hand side of $(p+2\gamma)\int_0^{\underline{q}(\gamma)} xf(x)dx = \gamma\mu$ with respect to γ:

$$
\begin{aligned}
\frac{d}{d\gamma}\left[(p+2\gamma)\int_0^{\underline{q}(\gamma)} xf(x)dx\right] &= 2\int_0^{\underline{q}(\gamma)} xf(x)dx + (p+2\gamma)\underline{q}(\gamma)f(\underline{q}(\gamma))\underline{q}'(\gamma)\\
&= 2\int_0^{\underline{q}(\gamma)} xf(x)dx + \underline{q}(\gamma)\frac{[1-\bar{w}'(\gamma)](p+2\gamma)-2[p-\bar{w}(\gamma)+\gamma]}{p+2\gamma}\\
&= 2\int_0^{\underline{q}(\gamma)} xf(x)dx + \underline{q}(\gamma)[1-\bar{w}'(\gamma)] - \frac{2\underline{q}(\gamma)[p-\bar{w}(\gamma)+\gamma]}{p+2\gamma}\\
&= \left[2qF(q) - 2\int_0^q F(x)dx + q - 2qF(q) - q\bar{w}'(\gamma)\right]_{q=\underline{q}(\gamma)}\\
&= \left[-2\int_0^q F(x)dx + q - q\bar{w}'(\gamma)\right]_{q=\underline{q}(\gamma)},
\end{aligned}
$$

where the second equation is from $F(\underline{q}(\gamma)) = \frac{p-\bar{w}(\gamma)+\gamma}{p+2\gamma} \Longrightarrow f(\underline{q}(\gamma))\underline{q}'(\gamma) = \frac{[1-\bar{w}'(\gamma)](p+2\gamma)-2[p-\bar{w}(\gamma)+\gamma]}{(p+2\gamma)^2}$ and the fourth equation is from $F(\underline{q}(\gamma)) = \frac{p-\bar{w}(\gamma)+\gamma}{p+2\gamma}$ and integration by parts. From the fact that the derivative of the right-hand side of $(p+2\gamma)\int_0^{\underline{q}(\gamma)} xf(x)dx = \gamma\mu$ with respect to γ is μ, we have $\left[-2\int_0^q F(x)dx + q - q\bar{w}'(\gamma)\right]_{q=\underline{q}(\gamma)} = \mu \Longrightarrow \left[-2\int_0^q F(x)dx + q - \mu\right]_{q=\underline{q}(\gamma)} = q\,\bar{w}'(\gamma)$, where we note that $-2\int_0^q F(x)dx + q - \mu = \int_0^q \bar{F}(x)dx - \mu - \int_0^q F(x)dx < 0$ because $q = \int_0^q dx$ and $\mu = \int_0^\infty \bar{F}(x)dx$. As a result, $\bar{w}'(\gamma) \le 0$.

Third, the retailer's order is $F^{-1}(\hat{\beta}(\gamma))$ for the wholesale price $w = c$. From these three observations, there is a one-to-one mapping from $w \in [c, \bar{w}(\gamma)]$ to $q \in [\underline{q}(\gamma), F^{-1}(\hat{\beta}(\gamma))]$. Because $w = \bar{F}(q)(p+2\gamma) - \gamma$ in the equilibrium, we can conclude.

Proof of Lemma 3.

a. If $\bar{w}(\gamma) = 0$, then $\bar{F}(\underline{q}(\gamma)) = \frac{\gamma}{p+2\gamma}$ and $\frac{\int_0^{\underline{q}(\gamma)} xf(x)dx}{\bar{F}(\underline{q}(\gamma))} = \mu$, which follows from $\int_0^{\underline{q}(\gamma)} xf(x)dx = \frac{\gamma\mu}{p+2\gamma}$. Define $H(q) \equiv \frac{\int_0^q xf(x)dx}{\bar{F}(q)}$. Then, $H'(q) = \frac{qf(q)\bar{F}(q)+f(q)\int_0^q xf(x)dx}{\bar{F}^2(q)} > 0$, $H(0) = 0$, and $H(\infty) > \mu$. Consequently, $H(q) = \mu$ has a unique solution $q = \underline{q}(\gamma)$ for $\gamma < \infty$. (i) This means that there exists a unique $\gamma(< \infty)$ such that $\bar{w}(\gamma) = 0$. Moreover, (ii) $\bar{w}'(\gamma) \le 0$ (Lemma 2b), and (iii) $\bar{w}(\gamma = 0) = p > c$. From (i)-(iii), there exists a unique $\bar{\gamma}(<\infty)$ such that the supplier's problem has feasible solutions, that is, $c \le \bar{w}(\gamma)$ when $\gamma \le \bar{\gamma}$.
b. From part (a), when $\gamma \le \bar{\gamma}$, the supplier's problem in (2) becomes

$$\max_{w\in[c,\,\bar{w}(\gamma)]} (w-c)\hat{q}_d(\gamma, w), \tag{A2}$$

where $\hat{q}_d(\gamma, w) = \bar{F}^{-1}(\frac{w+\gamma}{p+2\gamma})$. We make three observations for (A2). First, $\frac{\partial \hat{q}_d(\gamma, w)}{\partial w} < 0$ when $c \le w \le \bar{w}(\gamma)$ (Lemma 2a). Second, for the wholesale price $w = \bar{w}(\gamma)$, the retailer's order is $\underline{q}(\gamma)$.

Proof of Proposition 1. In this proof and the remainder, we use the notation $\bar{G}(\cdot) = 1 - G(\cdot)$. For the objective function $\pi_S(\gamma, q) \equiv \left[\bar{F}(q)(p+2\gamma) - \gamma - c\right]q$ in (4), because $g'(q) \ge 0$,

$$
\begin{aligned}
\left.\frac{\partial \pi_S^2(\gamma, q)}{\partial q^2}\right|_{\frac{\partial \pi_S(\gamma,q)}{\partial q}=0} &= (p+2\gamma)[-g'(q)\bar{F}(q) - (1-g(q))f(q)]\\
&= (p+2\gamma)\left[-g'(q)\bar{F}(q) - \frac{\bar{G}(q)}{\bar{F}(q)}f(q)\right]\\
&= (p+2\gamma)\left[-g'(q)\bar{F}(q) - \frac{(\gamma+c)}{(p+2\gamma)\bar{F}(q)}f(q)\right]\\
&\le 0,
\end{aligned}
$$

where $\frac{\partial \pi_S(\gamma, q)}{\partial q} = (p+2\gamma)\bar{G}(q) - \gamma - c$. Thus, for any given regret parameter γ, the supplier's profit $\pi_S(\gamma, q)$ is unimodal in q, implying the optimal solution to (4) exists and is unique.

Moreover, the first-order condition of (4) yields $G(q) = \hat{\beta}(\gamma) \Longrightarrow q = G^{-1}(\hat{\beta}(\gamma))$. Because $G(\cdot) \ge F(\cdot)$, then $G^{-1}(\hat{\beta}(\gamma)) \le F^{-1}(\hat{\beta}(\gamma))$. As a result, if the first-order condition yields a solution q such that $q \ge \underline{q}(\gamma)$, then q is optimal. Otherwise, the optimal solution is the corner solution $\underline{q}(\gamma)$.

We next show that $q \ge \underline{q}(\gamma)$ if and only if $G(q) \ge G(\underline{q}(\gamma))$. We make two observations. (i) First, since the derivative of $\bar{G}(q)$ with respect to q is:

$$\bar{G}'(q) = -g_D'(q)\bar{F}(q) - (1-g_D(q))f(q) = -g_D'(q)\bar{F}(q) - \frac{\bar{G}(q)}{\bar{F}(q)}f(q). \tag{A3}$$

If $\bar{G}(q) = \bar{F}(q) - qf(q) > 0$, then $\bar{G}'(q) < 0$ from $g_D'(q) > 0$, $f(q) \ge 0$ and $\bar{F}(q) \ge 0$. Thus, $\bar{G}(q)$ begins to decrease starting $q = 0$ because $\bar{G}(q)$ is continuous and $\bar{G}(0) = \bar{F}(0) = 1 > 0$. (ii) Second, from (A3), $\bar{G}'(q) < 0$ when $G(q) = 0$. This means that once $\bar{G}(q)$ reaches zero it will always to be less than or equal to zero. Combining $\bar{G}(\infty) = -\infty$ and (i)–(ii), we conclude that $\bar{G}(q)$ is decreasing in q as $\bar{G}(q) \geq 0$. This implies that $q \geq \underline{q}(\gamma)$ if and only if $\bar{G}(q) \leq \bar{G}(\underline{q}(\gamma)) \Longleftrightarrow G(q) \geq G(\underline{q}(\gamma))$.

Proof of Proposition 2.

a. From (5), the equilibrium order quantity q in NBE is such that $G(q) = \hat{\beta}(\gamma)$, where $\beta'(\gamma) = -\frac{p-2c}{(p+2\gamma)^2} < 0 \Longleftrightarrow p \geq 2c \Longleftrightarrow \beta \geq 1/2$. Because $G'(q) \geq 0$ when $\bar{G}(q) \geq 0$ (the proof of Lemma 1), then the equilibrium order quantity $\hat{q}_d(\gamma)$ increases in γ if and only if $\beta \leq 1/2$.
b. From (5), in BE, the equilibrium order $\underline{q}(\gamma)$ is such that $\int_0^{\underline{q}(\gamma)} xf(x)dx = \frac{\gamma\mu}{p+2\gamma}$. From $\frac{d}{d\gamma}[\frac{\gamma\mu}{p+2\gamma}] = \frac{\mu p}{(p+2\gamma)^2} > 0$, we can conclude that $\underline{q}(\gamma)$ increases in γ.

Proof of Proposition 3.

a. For the NBE case of the supply chain's profit in (6),
$$\pi'_T(\gamma) = [p\bar{F}(\hat{q}_d(\gamma)) - c]\hat{q}'_d(\gamma) = p\left[\hat{q}_d(\gamma)f(\hat{q}_d(\gamma)) + \frac{\gamma(1-2c/p)}{p+2\gamma}\right]\hat{q}'_d(\gamma),$$
where the second equality is from $G(\hat{q}_d(\gamma)) = \hat{\beta}(\gamma) \Longrightarrow \bar{F}(\hat{q}_d(\gamma)) = \frac{c+\gamma}{p+2\gamma} + \hat{q}_d(\gamma)f(\hat{q}_d(\gamma))$; see (5). Thus, when $\beta > 1/2$, $\hat{q}'_d(\gamma) < 0$ (Proposition 2a) implying that $\pi'_T(\gamma) \leq 0$.
b. For the BE case of supply chain profit, $\pi'_T(\gamma) = [p\bar{F}(\hat{q}_d(\gamma)) - c]\hat{q}'_d(\gamma) = \frac{[\bar{w}(\gamma)-c]p+\gamma(p-2c)}{p+2\gamma}\hat{q}'_d(\gamma)$, where the second equality is from $\bar{F}(\hat{q}_d(\gamma)) = \frac{\bar{w}(\gamma)+\gamma}{p+2\gamma}$. Thus, from Proposition 2b, $q'_d(\gamma) \geq 0$ implying that $\pi'_T(\gamma) \geq 0$ when $\beta > 1/2$.

The Case with Uniform Demand $U[0, b]$. From the definition of $\underline{q}(\gamma)$ in Lemma 2, we obtain $\int_0^{\underline{q}(\gamma)} xf(x)dx = \int_0^{\underline{q}(\gamma)} \frac{x}{b}dx = \frac{\underline{q}^2(\gamma)}{2b} \Longrightarrow \underline{q}(\gamma) = b\sqrt{\frac{\gamma}{p+2\gamma}}$ because $\frac{\gamma\mu}{p+2\gamma} = \frac{\gamma b}{2(p+2\gamma)}$ for the uniform demand.

Given this, we derive $\bar{\gamma}$ defined in Lemma 3a. $F(\underline{q}(\gamma)) = \frac{p-c+\gamma}{p+2\gamma} \Longleftrightarrow \sqrt{\frac{\gamma}{p+2\gamma}} = \frac{p-c+\gamma}{p+2\gamma} \Longleftrightarrow \gamma^2 + \gamma(2c-p) + 2cp - p^2 - c^2 = 0 \Longleftrightarrow \gamma = \frac{p-2c+\sqrt{8c^2-12cp+5p^2}}{2}$, where the last equivalence is from $\frac{p-2c-\sqrt{8c^2-12cp+5p^2}}{2} < 0 < \gamma$. Thus, $\bar{\gamma} = \frac{p-2c+\sqrt{8c^2-12cp+5p^2}}{2}$.

We now derive the equilibrium order quantity $\hat{q}_d(\gamma)$ in Equation (5). First, $G(\underline{q}(\gamma)) \geq \hat{\beta}(\gamma) \Longleftrightarrow 7\gamma^2 + \gamma(2c+2p) + 2cp - p^2 - c^2 \geq 0 \Longleftrightarrow \gamma \geq \frac{2\sqrt{2c^2-3cp+2p^2}-c-p}{7}$ because $\frac{-2\sqrt{2c^2-3cp+2p^2}-c-p}{7} < 0$. Second, $G^{-1}(\hat{\beta}(\gamma)) = \frac{(p-c+\gamma)b}{2(p+2\gamma)}$. Consequently, the equilibrium order quantity is

$$\hat{q}_d(\gamma) = \begin{cases} b\sqrt{\dfrac{\gamma}{p+2\gamma}} & \text{if } \gamma > \dfrac{2\sqrt{2c^2-3cp+2p^2}-c-p}{7} \\ \dfrac{b(p-c+\gamma)}{2(p+2\gamma)} & \text{if } \gamma \leq \dfrac{2\sqrt{2c^2-3cp+2p^2}-c-p}{7} \end{cases}. \tag{A4}$$

That is, if the regret bias is relatively low ($\gamma \leq \frac{2\sqrt{2c^2-3cp+2p^2}-c-p}{7}$), the equilibrium is non-binding. Otherwise, the equilibrium is binding.

Proof of Lemma 4.

a. When $\gamma = 0$, $F(\hat{q}_d(\gamma)) = \frac{p-w}{p} < \frac{p-c}{p} = F(q^*)$. Thus, $q^* > \hat{q}_d(\gamma)$.
b. When $\gamma = \bar{\gamma}$, $\bar{w}(\gamma) = c$. Thus, $\hat{q}_d(\bar{\gamma}) \geq q^*$ if and only if $\beta \leq 1/2$ from Lemma 1a.

Proof of Proposition 4. From Lemma 4, $\hat{q}_d(\gamma = \bar{\gamma}) > q^* > \hat{q}_d(\gamma = 0)$. Thus, there exists some regret level $\gamma^*(<\bar{\gamma})$ such that $\hat{q}_d(\gamma^*) = q^*$ because $\hat{q}_d(\gamma)$ is continuous in γ.

We can also obtain the value of the coordinating regret γ^*. In the NBE case, solving $G(q) = \hat{\beta}(\gamma)$ and $F(q) = \beta$ together, we get $qf(q) = \hat{\beta}(\gamma) - \beta$ and consequently $g_D(q) = \frac{qf(q)}{\bar{F}(q)} = \frac{\hat{\beta}(\gamma)-\beta}{1-\beta} = \frac{(2c-p)\gamma}{c(p+2\gamma)} \Longrightarrow \gamma^* = \frac{cpg_D(q)}{2c[1-g_D(q)]-p} = \frac{cg_D(q)}{2(1-\beta)[1-g_D(q)]-1}$. In the BE case, solving $\int_0^q xf(x)dx = \frac{\gamma\mu}{p+2\gamma}$ and $F(q) = \beta$ together, we find $\gamma^* = \frac{p\int_0^{F^{-1}(\beta)} xf(x)dx}{\mu - 2\int_0^{F^{-1}(\beta)} xf(x)dx}$.

Proof of Proposition 5.

a. In the BE case, $\hat{w}_d(\gamma) = \bar{w}(\gamma)$. Thus, $\hat{w}'_d(\gamma) \leq 0$ from Lemma 2c.
b. In NBE case, the equilibrium wholesale price $\hat{w}_d(\gamma) = p + \gamma - (p+2\gamma)F(\hat{q}_d(\gamma))$. Then,

$$\begin{aligned}\hat{w}_d'(\gamma) &= -(p+2\gamma)f(\hat{q}_d(\gamma))\hat{q}_d'(\gamma)+1-2F(\hat{q}_d(\gamma))\\ &= \frac{(p-2c)f(\hat{q}_d(\gamma))+[1-2F(\hat{q}_d(\gamma))](p+2\gamma)G'(\hat{q}_d(\gamma))}{(p+2\gamma)G'(\hat{q}_d(\gamma))}\\ &= \frac{-\left[1-2F(\hat{q}_d(\gamma))-2\hat{q}_d(\gamma)f(\hat{q}_d(\gamma))\right]f(\hat{q}_d(\gamma))+[1-2F(\hat{q}_d(\gamma))][2f(\hat{q}_d(\gamma))+qf'(\hat{q}_d(\gamma))]}{G'(\hat{q}_d(\gamma))}\\ &= \frac{\left[1-2F(\hat{q}_d(\gamma))\right][f(\hat{q}_d(\gamma))+\hat{q}_d(\gamma)f'(\hat{q}_d(\gamma))]+2\hat{q}_d f^2(\hat{q}_d(\gamma))}{G'(\hat{q}_d(\gamma))},\end{aligned}$$

where the second equality is from $G(\hat{q}(\gamma))=\hat{\beta}(\gamma)\Longrightarrow G'(\hat{q}(\gamma))\hat{q}'(\gamma)=\frac{2c-p}{(p+2\gamma)^2}$, and the third equality is from $\frac{p-2c}{p+2\gamma}=1-2\frac{c+\gamma}{p+2\gamma}=1-2\bar{G}(q)$ when $q=\hat{q}_d(\gamma)$. By the definition of IGFR, we have $f(x)+xf'(x)\geq-\frac{xf^2(x)}{\bar{F}(x)}$ for any $x\geq 0$. Thus, if $F(\hat{q}_d(\gamma))\leq 1/2$, then

$$\begin{aligned}\hat{w}_d'(\gamma) &\geq \frac{\left[1-2F(\hat{q}_d(\gamma))\right][-\frac{\hat{q}_d(\gamma)f^2(\hat{q}_d(\gamma))}{\bar{F}(\hat{q}_d)}]+2\hat{q}_d f^2(\hat{q}_d(\gamma))}{G'(\hat{q}_d(\gamma))}\\ &= \frac{\hat{q}_d(\gamma)f^2(\hat{q}_d(\gamma))}{\bar{F}(\hat{q}_d(\gamma))G'(\hat{q}_d(\gamma))}>0,\end{aligned}$$

where the inequality is from $G'(\hat{q}_d(\gamma))>0$ (the proof of Lemma 1). By the proof of Lemma 1, $\hat{w}_d'(\gamma)>0$ when $F(\hat{q}_d(\gamma))\leq 1/2 \Longleftrightarrow \hat{q}_d(\gamma)\leq F^{-1}(1/2)\Longleftrightarrow G(F^{-1}(1/2))\geq G(\hat{q}_d(\gamma))=\hat{\beta}(\gamma)\Longleftrightarrow 1/2+F^{-1}(1/2)f(F^{-1}(1/2))\geq\hat{\beta}(\gamma)$.

Proof of Proposition 6. For the supplier's equilibrium profit in Equation (A2), by the Envelop Theorem, $\pi_S'(\gamma)\geq 0\Longleftrightarrow\frac{\partial\hat{q}_d(\gamma,w)}{\partial\gamma}\Big|_{w=\hat{w}_d(\gamma)}\geq 0$ because $\hat{w}_d(\gamma)>c$. Consequently, $\pi_S'(\gamma)>0\Longleftrightarrow F(\hat{q}_d(\gamma))<1/2\Longleftrightarrow\hat{q}_d(\gamma)<F^{-1}(1/2)$ from Lemma 1. We next check the condition under which $\hat{q}_d(\gamma)<F^{-1}(1/2)$ holds.

a. In the NBE case, $\hat{q}_d(\gamma)<F^{-1}(1/2)\Longleftrightarrow G(F^{-1}(1/2))>G(\hat{q}_d(\gamma))=\hat{\beta}(\gamma)\Longleftrightarrow\hat{\beta}(\gamma)<\mathcal{B}$ from the proof of Lemma 1.
b. In the BE case, the equilibrium order quantity $\hat{q}_d(\gamma)=\underline{q}(\gamma)$ satisfies $\int_0^{\hat{q}_d(\gamma)}xf(x)dx=\frac{\gamma\mu}{p+2\gamma}$. Thus, $\hat{q}_d(\gamma)<F^{-1}(1/2)\Longleftrightarrow\frac{\gamma\mu}{p+2\gamma}<\int_0^{F^{-1}(1/2)}xf(x)dx\Longleftrightarrow\gamma\mu<(p+2\gamma)\int_0^{F^{-1}(1/2)}xf(x)dx\Longleftrightarrow[\mu-2\int_0^{F^{-1}(1/2)}xf(x)dx]\gamma<p\int_0^{F^{-1}(1/2)}xf(x)dx$. Note that

$$\begin{aligned}\mu-2\int_0^{F^{-1}(1/2)}xf(x)dx &= \int_0^{\infty}\bar{F}(x)dx-\left[F^{-1}(1/2)-2\int_0^{F^{-1}(1/2)}F(x)dx\right]\\ &= \int_0^{F^{-1}(1/2)}\bar{F}(x)dx+\int_{F^{-1}(1/2)}^{\infty}\bar{F}(x)dx+2\int_0^{F^{-1}(1/2)}F(x)dx-F^{-1}(1/2)\\ &= \int_{F^{-1}(1/2)}^{\infty}\bar{F}(x)dx+\int_0^{F^{-1}(1/2)}F(x)dx\\ &>0,\end{aligned}$$

where the first equality is from the integration by parts. Thus, $\pi_S'(\gamma)\geq 0$ when $\gamma<\mathcal{L}$.

Justification of $\gamma<\mathcal{L}$ in BE Case for the Uniform Demand $U[0,b]$. For the uniform demand, it is the binding equilibrium when $\gamma\leq\frac{2\sqrt{2c^2-3cp+2p^2}-c-p}{7}\Longleftrightarrow\frac{\gamma}{p}\leq\frac{2\sqrt{2k^2-3k+2}-k-1}{7}$, where $k=\frac{c}{p}$. Because $\frac{2\sqrt{2k^2-3k+2}-k-1}{7}$ decreases in k, in the BE case, $\gamma\leq\frac{2\sqrt{2c^2-3cp+2p^2}-c-p}{7}\Big|_{k=0}=\frac{(2\sqrt{2}-1)p}{7}<\mathcal{L}$, where $\mathcal{L}=p/2$.

Proof of Proposition 7.

a. In the BE case, we know that the retailer's objective function $p\mathbb{E}[D\wedge\hat{q}_d(\gamma)]-\hat{w}_d(\gamma)\hat{q}_d(\gamma)-\gamma\mathbb{E}[|\hat{q}_d(\gamma)-D|]=0$. Thus, the retailer's profit $\pi_R(\gamma)=\gamma\mathbb{E}[|\hat{q}_d(\gamma)-D|]=\gamma[\int_0^{\hat{q}_d(\gamma)}(\hat{q}_d(\gamma)-x)f(x)dx+\int_{\hat{q}_d(\gamma)}^{\infty}[x-\hat{q}_d(\gamma)]f(x)dx]$. Thus, $\pi_R'(\gamma)=\mathbb{E}[|\hat{q}_d(\gamma)-D|]+\gamma[F(\hat{q}_d(\gamma))-\bar{F}(\hat{q}_d(\gamma))]\hat{q}_d'(\gamma)>0$ when $F(\hat{q}_d(\gamma))>1/2\Longleftrightarrow\gamma>\mathcal{L}$.
b. In the NBE case, it suffices to consider $\gamma=0$. Define $\pi_R(\gamma,w)=p\mathbb{E}[D\wedge q]-wq$. Then, the newsvendor retailer's profit

$$\begin{aligned}\pi_R'(\gamma=0) &= \frac{\partial\pi_R(\gamma,w)}{\partial\gamma}\Big|_{w=\hat{w}(\gamma),\gamma=0}+\frac{\partial\pi_R(\gamma,w)}{\partial w}\Big|_{w=\hat{w}(\gamma),\gamma=0}\hat{w}'(\gamma)\\ &= \frac{\gamma[p-2\hat{w}(\gamma)]}{p+2\gamma}\frac{\partial\hat{q}(\gamma,\hat{w}(\gamma))}{\partial\gamma}\Big|_{\gamma=0}-\left[\hat{q}(\gamma,\hat{w}(\gamma))\right]_{\gamma=0}\hat{w}'(\gamma)\\ &= -\left[\hat{q}(\gamma,\hat{w}(\gamma))\hat{w}'(\gamma)\right]_{\gamma=0}.\end{aligned}$$

Thus, $\pi_R'(\gamma=0)>0$ holds when $\hat{w}'(\gamma=0)<0$. From the proof of Proposition 5b, when $\gamma=0$,

$$\hat{w}'_d(\gamma) = \left.\frac{\left[1-2F(\hat{q}_d(\gamma))\right]\left[f(\hat{q}_d(\gamma))+\hat{q}_d(\gamma)f'(\hat{q}_d(\gamma))\right]+2\hat{q}_d f^2(\hat{q}_d(\gamma))}{G'(\hat{q}_d(\gamma))}\right|_{\gamma=0}.$$

Note that when β is closed to one, $\hat{q}_d(\gamma=0)=0$. Thus, $\hat{w}'_d(\gamma)<0$. As a result, $\pi'_R(\gamma=0)<0$. From the continuity of the newsvendor profit, $\pi_R(\gamma)$ decreases in γ around $\gamma=0$.

Proof of Example 1. Because $q(\gamma)=(p/\gamma+2)^{-\frac{1}{k+1}}$ from Lemma 2, $\bar{\gamma}$ defined in Lemma 3 satisfies $(p-c+\bar{\gamma})^{1+k}=(p+2\bar{\gamma})\bar{\gamma}^k$. The equilibrium order quantity in (5) is

$$\hat{q}_d(\gamma)=\begin{cases}\left(\frac{p}{\gamma}+2\right)^{-\frac{1}{k+1}} & \text{if } (p-c+\gamma)^{1+k}<(p+2\gamma)\gamma^k(1+k)^{1+k}\\ \left(\frac{p-c+\gamma}{(p+2\gamma)(1+k)}\right)^{\frac{1}{k}} & \text{if } (p-c+\gamma)^{1+k}\geq(p+2\gamma)\gamma^k(1+k)^{1+k}.\end{cases} \quad \text{(A5)}$$

Moreover, from the definition of $\mathcal{L}$ and $\mathcal{B}$, we have $\mathcal{L}=p/(2^{1+1/k}-2)$ and $\mathcal{B}=(1+k)/2$.

Note

[1]In this study, we use increasing and decreasing in a weakly sense.

References

Bell, D. E. 1982. Regret in decision making under uncertainty. *Oper. Res.* **30**(5): 961–981.

Bell, D. E. 1983. Risk premiums for decision regret. *Management Sci.* **29**(10): 1156–1166.

Bostian, A. J. A., C. A. Holt, A. M. Smith. 2008. Newsvendor "pull-to-center" effect: Adaptive learning in a laboratory experiment. *Manuf. Serv. Oper. Manag.* **10**(4): 590–608.

Cachon, G. P. 2003. Supply chain coordination with contracts. *Handbooks Oper. Res. Manag. Sci.* **11**: 227–339.

Choi, T.-M., S. W. Wallace, Y. Wang. 2018. Big data analytics in operations management. *Prod. Oper. Manag.* **27**(10): 1868–1883.

Cohen, M. C. 2018. Big data and service operations. *Prod. Oper. Manag.* **27**(9): 1709–1723.

Cui, R., M. Li, S. Zhang. 2021. AI and procurement. *Manuf. Serv. Oper. Manag.* Forthcoming.

Davis, A. M., E. Katok, N. Santamaría. 2014. Push, pull, or both? A behavioral study of how the allocation of inventory risk affects channel efficiency. *Management Sci.* **60**(11): 2666–2683.

Dietvorst, B. J., J. P. Simmons, C. Massey. 2015. Algorithm aversion: People erroneously avoid algorithms after seeing them err. *J. Exp. Psychol. Gen.* **144**(1): 114.

Dietvorst, B. J., J. P. Simmons, C. Massey. 2018. Overcoming algorithm aversion: People will use imperfect algorithms if they can (even slightly), modify them. *Management Sci.* **64**(3): 1155–1170.

Engelbrecht-Wiggans, R., E. Katok. 2008. Regret and feedback information in first-price sealed-bid auctions. *Management Sci.* **54**(4): 808–819.

Filiz-Ozbay, E., E. Y. Ozbay. 2007. Auctions with anticipated regret: Theory and experiment. *Am. Econ. Rev.* **97**(4): 1407–1418.

Fisher, M., A. Raman. 2010. *The New Science of Retailing: How Analytics are Transforming the Supply Chain and Improving Performance*. Harvard Business Review Press, Brighton.

Katok, E., D. Y. Wu. 2009. Contracting in supply chains: A laboratory investigation. *Management Sci.* **55**(12): 1953–1968.

Kumar, S., V. Mookerjee, A. Shubham. 2018. Research in operations management and information systems interface. *Prod. Oper. Manag.* **27**(11): 1893–1905.

Lariviere, M. A., E. L. Porteus. 2001. Selling to the newsvendor: An analysis of price-only contracts. *Manuf. Serv. Oper. Manag.* **3**(4): 293–305.

Li, M. 2019. Overconfident distribution channels. *Prod. Oper. Manag.* **28**(6): 1347–1365.

Li, M., Y. Liu. 2021. Managerial regret and inventory pricing. *Management Sci.* Forthcoming.

Li, M., N. C. Petruzzi. 2017. Demand uncertainty reduction in decentralized supply chains. *Prod. Oper. Manag.* **26**(1): 156–161.

Li, M., N. C. Petruzzi, J. Zhang. 2016. Overconfident competing newsvendors. *Management Sci.* **63**(8): 2637–2646.

Nasiry, J., I. Popescu. 2012. Advance selling when consumers regret. *Management Sci.* **58**(6): 1160–1177.

Olsen, T. L., B. Tomlin. 2020. Industry 4.0: opportunities and challenges for operations management. *Manuf. Serv. Oper. Manag.* **22**(1): 113–122.

Özer, Ö., Y. Zheng. 2016. Markdown or everyday low price? The role of behavioral motives. *Management Sci.* **62**(2): 326–346.

Schweitzer, M. E., G. P. Cachon. 2000. Decision bias in the newsvendor problem with a known demand distribution: Experimental evidence. *Management Sci.* **46**(3): 404–420.

Spengler, J. J. 1950. Vertical integration and antitrust policy. *J. Polit. Econ.* **58**(4): 347–352.

Van Donselaar, K. H., V. Gaur, T. Van Woensel, R. A. Broekmeulen, J. C. Fransoo. 2010. Ordering behavior in retail stores and implications for automated replenishment. *Management Sci.* **56**(5): 766–784.