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Shortages of perishables control for a stochastic inventory system in retail through dynamic pricing with an adjustable factor

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Abstract. This paper examines an inventory system of a perishable product facing compound Poisson demand with price-dependent intensity. The proposed model includes an adjustable factor that influences the intensity of demand and, consequently, the possibility of shortages. By employing diffusion approximation of the inventory level process, stochastic properties of the selling process are obtained, and the expected revenue is derived with a penalty for the shortages. Consideration of the shortages' period allows us to expand the scope of applicability the linear approximation of a dependence of demand intensity on price.

Keywords: dynamic pricing; price sensitive demand; compound Poisson demand; adjustable factor; diffusion approximation; shortages.

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Научная статья
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Контроль дефицита скоропортящихся товаров в розничной торговле посредством динамического ценообразования с регулирующим коэффициентом

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Аннотация. Рассматривается система управления запасами скоропортящегося товара при спросе, описываемом составным пуассоновским процессом с интенсивностью, зависящей от цены. Предлагаемая модель включает в себя регулирующий фактор, влияющий на интенсивность спроса и, следовательно, на возможность возникновения нехватки товара. В рамках диффузионной аппроксимации уровня запасов исследуются стохастические свойства процесса продаж и находится средняя выручка с учетом штрафа за нехватку товара. Введение периода нехватки товара позволяет расширить область применимости линейной аппроксимации зависимости интенсивности спроса от цены.

Ключевые слова: динамическое ценообразование; чувствительный к цене спрос; составной пуассоновский спрос; регулирующий коэффициент; диффузионная аппроксимация; нехватка товара.

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Introduction

Dynamic pricing has been extensively studied as a key strategy for managing perishable products, particularly within a finite selling horizon. Dynamic pricing, which involves continuously adjusting prices in response to time-dependent variables such as the remaining shelf life of the product and its inventory level, effectively addresses the challenge of perishability by aligning supply with temporally fluctuating demand. As emphasized in [1], such pricing strategies not only offer financial advantages to retailers but also lead to a substantial decline in waste, which is especially critical in the context of food products. A growing body of literature confirms that dynamic pricing mitigates the risk of unsold inventory and helps to avoid the inefficiencies associated with traditional static pricing approaches [2]. While extensive research has explored dynamic pricing mechanisms, the specific challenge of managing shortages has garnered focused attention in recent years, particularly those resulting in lost sales [3].

Recent studies have highlighted the value of dynamically adjusting prices not only to stimulate demand for aging inventory but also to control the sales rate in order to reduce the likelihood of stock outs during the selling period [4, 5]. In setting without replenishment opportunities, lost sales represent a critical concern, as unmet demand directly translates to revenue loss and diminished customer satisfaction. In [6], an integrated model of dynamic pricing and inventory control under a lost sales framework is proposed, highlighting that optimal pricing strategies must incorporate both the stochastic characteristics of demand and the perishability of goods. The importance of pricing strategies for addressing the risk of lost sales in perishable goods markets has been well recognized in recent studies [7, 8].

We proposed a basic stochastic dynamic price control model in [9], which allows us, triggering purchases, to sell all a perishable product at hand during its lifetime almost surely. In [10], a multiplicative adjustable factor was introduced into the basic model, which helps address the problem of fitting the demand rate to real-life situations and allows for customization of the sales process. In [11], we obtained optimal weight function approximation for large lot sizes that depends on a parameter and considered two close to optimal models of the dependence of demand intensity on price, controlling the shortages by changing the parameter. In this paper, we extend the model introduced in [10] by incorporating the moment of the shortages occurrence and the corresponding penalty in the expected revenue.

1. Problem statement

We commence by formulating the fundamental assumptions and mathematical framework. Suppose a supplier acquires an initial stock Q_0 per unit price d at the beginning of the sales cycle T, where additional procurement is prohibited during this period. Market demand adheres to a compound Poisson process governed by intensity $\lambda(c(t))$, with $c = c(t)$ representing the time-varying unit selling price. Individual customer purchases are treated as independent and identically distributed random variables, characterized by first-order moment a_1 and second-order moment a_2.

For analytical tractability, we employ a diffusion approximation of the inventory level process $Q(t)$, which follows the stochastic differential equation

$$dQ(t) = -a_1\lambda(c(t))dt + \sqrt{a_2\lambda(c(t))}dw(t),$$

where $w(\cdot)$ is the Wiener process.

We adopt the following pricing control:

$$a_1\lambda\left(c(t)\right) = \kappa\frac{Q(t)}{T-t}, \tag{1}$$

that is, the product's average sales rate and its instantaneous sales rate must be proportional; coefficient $\kappa > 0$. We will call control model (1) the linear one.

The idea of introducing adjustable factors into idealized dynamic pricing models in order to adapt to real market conditions as well as a lot of results in inventory control modelling belongs to Alexander Fedorovich Terpugov (1939-2009), former Head of the Department of Probability Theory and Mathematical Statistics at Tomsk State University, outstanding scientist and teacher.

It follows that the stock level process satisfies the following equation:

$$dQ(t) = -\kappa \frac{Q(t)}{T-t} dt + \sqrt{\kappa \frac{a_2}{a_1} \frac{Q(t)}{T-t}} dw(t) . \quad (2)$$

Below we use (2) to get the properties of the stock level process. Then we propose a heuristic method for determining the moment when the shortages occur, introduce appropriate penalties, and obtain the expected revenue with the penalties.

2. The stochastic properties of the selling process

Within the framework of the approximation, the expectation of the stock level process

$$E\{Q(t)\} = \bar{Q}(t) = Q_0 \left(1 - t/T\right)^{\kappa} . \quad (3)$$

Denote $\overline{Q^2}(t) = E\left\{Q^2(t)\right\}$. Applying Ito's formula and averaging, we get

$$\frac{d\overline{Q^2}}{dt} = -2\kappa \frac{\overline{Q^2}}{T-t} + \kappa \frac{a_2}{a_1} \frac{\bar{Q}}{T-t}$$

subject to $\overline{Q^2}(0) = Q_0^2$.

It follows that the variance of the stock level process

$$Var\{Q(t)\} = \frac{a_2}{a_1} Q_0 \left(1 - \frac{t}{T}\right)^{\kappa} \left(1 - \left(1 - \frac{t}{T}\right)^{\kappa}\right).$$

The second initial moment of $Q(\cdot)$

$$\overline{Q^2} = \frac{a_2}{a_1} Q_0 \left(1 - \frac{t}{T}\right)^{\kappa} \left[1 - \left(1 - \frac{t}{T}\right)^{\kappa}\right] + Q_0^2 \left(1 - \frac{t}{T}\right)^{2\kappa} . \quad (4)$$

By applying Ito's formula and the Laplace transform, we obtain the probability density function of the inventory level

$$f(q,t) = \exp\left(\frac{-\beta Q_0 \left(1 - t/T\right)^{\kappa}}{1 - \left(1 - t/T\right)^{\kappa}}\right) \left[\delta(q) + \beta \exp\left(\frac{-\beta Q_0}{1 - \left(1 - t/T\right)^{\kappa}}\right) \times \frac{\sqrt{\left(1 - t/T\right)^{\kappa} Q_0 / q}}{1 - \left(1 - t/T\right)^{\kappa}} I_1\left(\frac{2\beta\sqrt{\left(1 - t/T\right)^{\kappa} Q_0 q}}{1 - \left(1 - t/T\right)^{\kappa}}\right)\right], \quad (5)$$

where $\beta = 2a_1 / a_2$, $I_1(\cdot)$ is the first order modified Bessel function of the first kind, and $\delta(\cdot)$ represents the Dirac delta distribution.

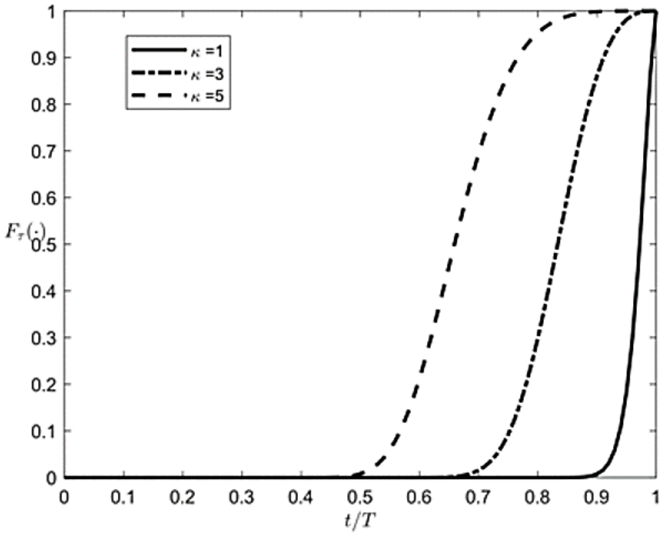

Fig. 1. $F_\tau(\cdot)$ dependence on t/T for κ = 1, 3, and 5

From (5) it follows that the cumulative distribution function of the length of time τ it takes to sell Q_0

$$F_\tau(t) = \exp\left(-\beta Q_0 \frac{(1-t/T)^\kappa}{1-(1-t/T)^\kappa}\right).$$

Thus, $F_\tau(T)=1$, and the probability of the shortages increases when κ increases.

Figure 1 illustrates the behavior of $F_\tau(t)$ for $\beta Q_0 = 150$; κ = 1, 3, and 5.

The expectation of the selling duration τ

$$E\{\tau\} = \int_0^T (1-F_\tau(t))dt = T\left(1-\int_0^1 \exp\left(-\beta Q_0 \frac{z^\kappa}{1-z^\kappa}\right)dz\right).$$

For $\beta Q_0 >> 1$, we get

$$E\{\tau\} \approx T\left(1-\int_0^1 \exp\left(-\beta Q_0 z^\kappa\right)dz\right) = T\left(1-\frac{1}{\kappa(\beta Q_0)^{1/\kappa}}\int_0^\infty u^{(1-\kappa)/\kappa} e^{-u} du\right) = T\left(1-\frac{\Gamma((\kappa+1)/\kappa)}{(\beta Q_0)^{1/\kappa}}\right), \tag{6}$$

where $\Gamma(\cdot)$ is the gamma function.

3. The expected revenue taking the shortages into account

We take (6) as the moment of the shortages occurrence T_1, $T_1 = Tx_0$, where $x_0 = 1-\frac{\Gamma((\kappa+1)/\kappa)}{(\beta Q_0)^{1/\kappa}}$, and $E\{Q(T_1)\} = \bar{Q}(T_1) = \frac{\Gamma^\kappa((\kappa+1)/\kappa)}{\beta}$. In the simulation, the moment of shortages occurs when the available stock is less than the quantity requested by the last consumer.

The simulation results for the duration of the selling period are presented in Figure 2 and are obtained through a thinning algorithm implementation of a non-homogeneous Poisson process simulation with 1,000 replications. Mean values are reported as the outcomes. The analysis employs parameter values in the range $1 \le \kappa \le 5$ and exams two distributions of purchases: uniformly distributed over (0,10) and exponentially distributed with parameter 5. The theoretical prediction (black curve) is compared with the simulated results for uniform (red curve) and exponential (blue curve) purchases distributions.

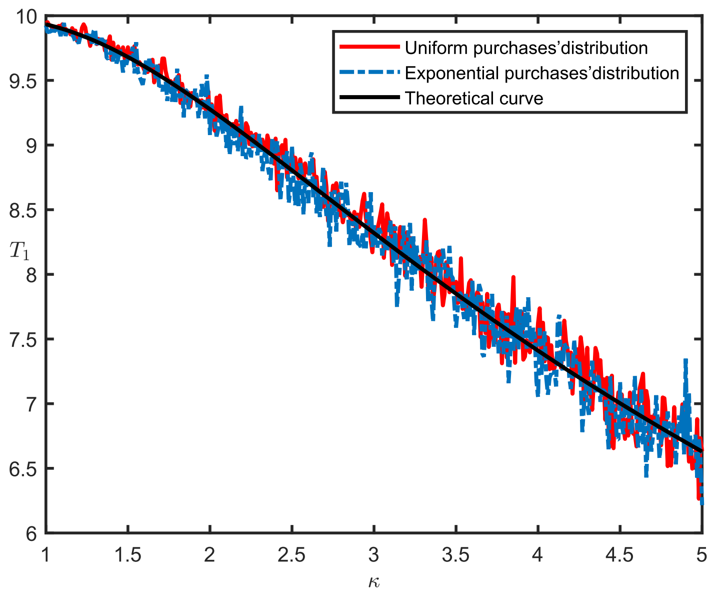

Fig. 2. T_1 dependence on κ; T = 10, Q_0 = 500, purchases are Uniform (0,10) or Exp (5)

Parameter κ has a significant impact on the shortages' duration. When $\kappa > 2$, the shortages period may exceed 10% of the total sales cycle length.

Let us consider linear approximation of the intensity-of-price dependence

$$\lambda(c) = \lambda_0 - \lambda_1 \frac{c(t) - c_0}{c_0}, \tag{7}$$

where c_0 denotes the basic price level associated with initial demand intensity λ_0, while $\lambda_1 > 0$ reflects the demand response to price deviations from its baseline. Linear price-demand relationships represent a standard modeling approach; see, for example, [12].

Combining (1) and (7) we get

$$c(t) = c_0 \left(1 + \frac{\lambda_0}{\lambda_1} - \frac{\kappa Q(t)}{a_1 \lambda_1 (T-t)}\right).$$

The average revenue per unit of time

$$E\{c(t) a_1 \lambda(c)\} = c_0 \kappa E\left\{\left(1 + \frac{\lambda_0}{\lambda_1} - \frac{\kappa}{a_1\lambda_1}\frac{Q(t)}{T-t}\right)\frac{Q(t)}{T-t}\right\} = c_0\left(1 + \frac{\lambda_0}{\lambda_1}\right)\kappa \frac{\bar{Q}}{T-t} - c_0 \frac{\kappa^2}{a_1\lambda_1}\frac{\overline{Q^2}}{(T-t)^2}.$$

Finally, taking into account (3) and (4) we get

$$E\{c(t) a_1 \lambda(c)\} = c_0\left(1 + \frac{\lambda_0}{\lambda_1}\right)\kappa \frac{Q_0}{T-t}\left(1 - \frac{t}{T}\right)^{\kappa} -$$

$$- \frac{c_0 \kappa^2 Q_0}{a_1 \lambda_1 (T-t)^2}\left(\frac{a_2}{a_1}\left(1 - \frac{t}{T}\right)^{\kappa}\left(1 - \left(1 - \frac{t}{T}\right)^{\kappa}\right) + \left(1 - \frac{t}{T}\right)^{2\kappa} Q_0\right).$$

Let us consider the expected revenue prior to shortages

$$\bar{S} = a_1 \int_0^{T_1} E\{c(t)\lambda(t)\}\, dt.$$

The three integrals below are straightforward to obtain:

$$\int_0^{T_1}\left(1 - \frac{t}{T}\right)^{\kappa}\frac{dt}{T-t} = \frac{1 - (1 - x_0)^{\kappa}}{\kappa};$$

$$\int_0^{T_1}\left(1 - \frac{t}{T}\right)^{\kappa}\frac{dt}{(T-t)^2} = \begin{cases} \dfrac{1 - (1 - x_0)^{\kappa - 1}}{T(\kappa - 1)} & \text{for } \kappa \neq 1; \\ -\dfrac{\ln(1 - x_0)}{T} & \text{for } \kappa = 1; \end{cases}$$

$$\int_0^{T_1}\left(1 - \frac{t}{T}\right)^{2\kappa}\frac{dt}{(T-t)^2} = \begin{cases} \dfrac{1 - (1 - x_0)^{2\kappa - 1}}{T(2\kappa - 1)} & \text{for } \kappa \neq \dfrac{1}{2}; \\ -\dfrac{\ln(1 - x_0)}{T} & \text{for } \kappa = \dfrac{1}{2}. \end{cases}$$

In particular, when $\kappa = 1$, the resulting model of retail price control (1) reduces to the form $a_1 \lambda(c(t)) = \frac{Q(t)}{T-t}$, which is the same as the basic model in [9]. Unlike the approach in [9], where the expected revenue is derived by considering small deviations of the price from its stationary value, in this paper, adjustable coefficient κ is introduced, which enables us to consider the linear dependence of the demand intensity on the price. The expected revenue for $\kappa = 1$ is as follows

$$\bar{S}_{\kappa=1} = c_0 Q_0\left(1 + \frac{\lambda_0}{\lambda_1}\right)\left(1 - \frac{1}{\beta Q_0}\right) + \frac{c_0 Q_0}{\lambda_1 T}\left(\frac{a_2}{a_1^2}\ln\left(\frac{1}{\beta Q_0}\right) + \left(\frac{a_2}{a_1^2} - \frac{Q_0}{a_1}\right)\left(1 - \frac{1}{\beta Q_0}\right)\right), \tag{8}$$

while the main part of the expected revenue of basic model in [9] $\bar{S}_{basic} = c_0 Q_0 \left(1 - \frac{\lambda_0}{\lambda_1}\frac{1}{\beta Q_0}\right)$.

The observed discrepancy can be attributed to two key aspects. First, here we introduce T_1 as the time point at which the shortages occur. Notably, our framework accommodates the possibility of shortages even when $\kappa = 1$; in this case, $T_1 = T\left(1 - \frac{1}{\beta Q_0}\right)$. This contrasts with the approach adopted in [9], where the selling period is T and a consideration of the shortages is not incorporated. Secondly, in [9] we employ only a linear part of Taylor expansion of product $c(t)\lambda(c(t))$.

For $\kappa > 1$ the expected revenue without taking into account the penalty for the shortages

$$\bar{S} = c_0 Q_0\left(1 + \frac{\lambda_0}{\lambda_1}\right)\left(1 - (1 - x_0)^{\kappa}\right) - \\ - \frac{c_0 Q_0 \kappa^2}{\lambda_1 T}\left(\frac{a_2}{a_1^2}\frac{1 - (1 - x_0)^{\kappa - 1}}{(\kappa - 1)} - \left(\frac{a_2}{a_1^2} - \frac{Q_0}{a_1}\right)\frac{1 - (1 - x_0)^{2\kappa - 1}}{(2\kappa - 1)}\right). \tag{9}$$

We adapt an assumption where unmet demand results in lost sales, and the demand intensity during stock out's period remains constant, defined by the intensity at moment T_1

$$\lambda(c(T_1)) = \kappa\frac{\bar{Q}(T_1)}{a_1(T - T_1)} = \kappa\frac{Q_0}{a_1 T}\left(\frac{\Gamma((\kappa + 1)/\kappa)}{(\beta Q_0)^{1/\kappa}}\right)^{\kappa - 1} = \kappa\frac{Q_0}{a_1 T}(1 - x_0)^{\kappa - 1};$$

analogously, the retail price during this period $c(T_1) = c_0\left(1 + \frac{\lambda_0}{\lambda_1} - \kappa\frac{Q_0}{a_1\lambda_1 T}(1 - x_0)^{\kappa - 1}\right)$.

We define the average lost sales as follows

$$\bar{S}_s = -a_1 c(T_1)\lambda(c(T_1))(T - T_1) = -c_0 Q_0 \kappa (1 - x_0)^{\kappa}\left(1 + \frac{\lambda_0}{\lambda_1} - \kappa\frac{Q_0}{a_1\lambda_1 T}(1 - x_0)^{\kappa - 1}\right).$$

Thus, the expected revenue for $\kappa > 1$

$$\bar{S}_{\kappa > 1} = c_0 Q_0\left(1 + \frac{\lambda_0}{\lambda_1}\right)\left(1 - (1 - x_0)^{\kappa}\right) - c_0 Q_0 \kappa (1 - x_0)^{\kappa}\left(1 + \frac{\lambda_0}{\lambda_1} - \kappa\frac{Q_0}{a_1\lambda_1 T}(1 - x_0)^{\kappa - 1}\right) - \\ - \frac{c_0 Q_0 \kappa^2}{\lambda_1 T}\left(\frac{a_2}{a_1^2}\frac{1 - (1 - x_0)^{\kappa - 1}}{(\kappa - 1)} - \left(\frac{a_2}{a_1^2} - \frac{Q_0}{a_1}\right)\frac{1 - (1 - x_0)^{2\kappa - 1}}{(2\kappa - 1)}\right). \tag{10}$$

The expected revenue is monotonically decreasing with respect to κ, and weighted revenue $\bar{S}_{\kappa > 1} / a_1 c_0$ depends on four dimensionless system's characteristics $Q_0 / a_1,\ \lambda_0 / \lambda_1, \lambda_1 T,\ a_2 / a_1^2,$ except κ. Ratio Q_0 / a_1 is connected with the number of purchases during the selling period, that is, the intensity of the demand; λ_0 / λ_1 reflects the relative base intensity of the demand in relation to its price sensitivity; $\lambda_1 T$ is the aggregate sensitivity of demand to price deviations within the selling period; and ratio a_2 / a_1^2 characterizes the coefficient of variation of the purchases.

In Figure 3, the results of simulation of weighted revenues dependence on κ are presented for different sets of the system's characteristics for uniform and exponential distributions of purchases, $T = 10$. The black curves represent the theoretical results, and the red curves are the simulation results.

Analogously the models in [11], Figure 3 demonstrates that increasing λ_0 / λ_1 and $\lambda_1 T$ leads to a significant increase in the revenue, and ratio a_2/a_1^2 that governs purchases' variation exhibits negligible influence on the revenue, as evidenced by the final two subplots. The theoretical revenues closely align with the simulated ones.

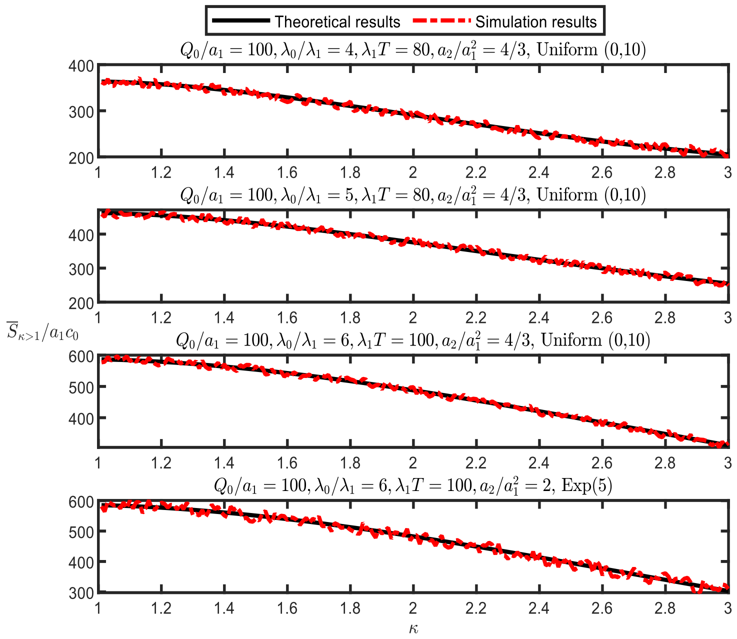

Fig. 3. $\bar{S}_{\kappa>1} / a_1 c_0$ dependence on κ, T = 10

The expected revenue curve is negatively correlated with adjustable factor κ and exhibits the opposite behaviour compared with the two near-optimal models in [11], where the expected revenue is positively correlated with parameter *C*. The expected revenues' maximums are achieved when the adjustable parameters are equal to 1.

The revenue of the linear model is a concave function with respect to Q_0/a_1. Figure 4 depicts weighted revenue $\bar{S}_{\kappa>1} / a_1 c_0$ dependence on Q_0/a_1 for κ = 1,2, 2, and 2,5; $\lambda_0 / \lambda_1 = 4$, $\lambda_1 T = 100$, $a_2 / a_1^2 = 4/3$.

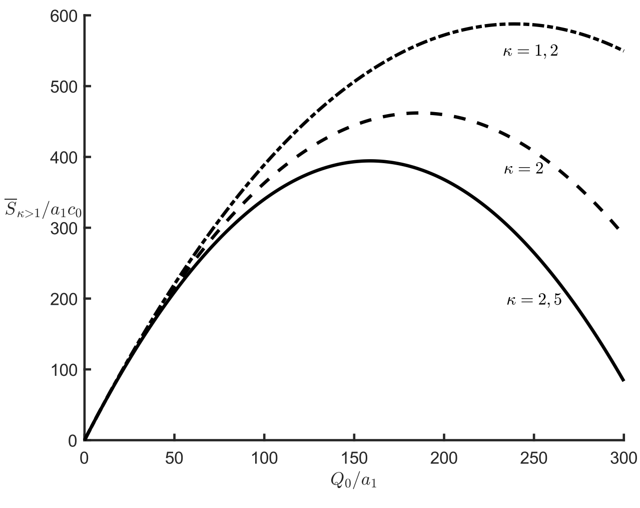

Fig. 4. $\bar{S}_{\kappa>1} / a_1 c_0$ dependence on Q_0 / a_1

As κ > 1 decreases, the duration of the shortages period also decreases, thereby mitigating associated penalties and enhancing the corresponding revenue.

Conclusion

The dynamic price control model proposed in this paper can control shortages by adjusting the factor κ. We derived the stochastic properties of the selling process and obtained the expected revenue that considers the penalties for the shortages treating unsatisfied demand as lost sales.

The expected revenue in (10) depends on four dimensionless system characteristics: Q_0 / a_1, $\lambda_0 / \lambda_1, \lambda_1 T$, a_2 / a_1^2. If the initial lot size satisfies natural condition $\lambda_0 T a_1 = Q_0$, then the number of the system characteristics are reduced to three, as ratio Q_0 / a_1 can be represented in terms of λ_0 / λ_1 and $\lambda_1 T$. These two values have a crucial influence on the revenue as Figure 3 demonstrates: an increase in λ_0 / λ_1 and $\lambda_1 T$ leads to a higher retail price and enhances the expected revenue.

Numerical analysis indicates that as the adjustable factor approaches 1 from above, the penalties incurred from stock out period reduced thereby enhancing revenue. The maximum revenue achieved when the adjustable factor is equal to 1, consistent with the two models in [11]. This result is quite natural, since the basic model ensures equality of instantaneous and average sales rates at any moment of the sales cycle, idealizing the situation. The papers related to the adjustable factors [10, 11, 13] aim to adapt the basic model to real life situations and to estimate the corresponding losses.

Our future research will focus on addressing more detailed numerical comparisons the proposed models under shortages and leftovers scenarios, in order to highlight their distinctive features and support their accurate application in practice.

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