Backordering policy for hi-tech products with price and demand uncertainty during the pandemics

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Abstract

The decline phase of a high-tech product's life cycle often causes variations in production schedules due to over or under production. To address this challenge, we propose a production-inventory model that considers decreasing demand and prices during pandemics. Our model aims to optimize replenishment, dispatching, and backordering policies, ultimately maximizing total profit for high-tech industries. Our proposed solution procedure derives optimal policies, taking into account the unique demands during the pandemics. We suggest adopting either a last-in-first-out (LIFO) or first-in-first-out (FIFO) backordering policy depending on whether profit or fairness is the primary concern. We have provided a numerical example and conducted a sensitivity analysis to demonstrate the practical application of the proposed model. By optimizing the replenishment, our model enables high-tech industries to maximize total profit, even in the face of declining demand and prices during the pandemics. Overall, our model represents a valuable tool for high-tech industries seeking to better manage production and inventory, and we believe it has the potential to increase product profitability during the declining phase of a product's life cycle.

Key words: high-tech products; dispatching policies; decreasing demand; decreasing prices; backordering policies

1. Introduction

As high-tech products approach the end of their life cycle, it is common for prices and demand to decrease rapidly. This is due to the fast pace of technological progress, which causes the cost of components and selling prices to decline at a rate of approximately 1% per week (Sern, [1]). As a result, there has been a growing interest in research on varying price and demand in recent decades.

Studies by Dave and Patel [2] and Hollier and Mak [3] have developed time-dependent models for perishable items that incorporate declining demand for fixed and variable restocking intervals. Mak [4] further established an optimal production-inventory policy with constant demand and partial backordering, while Wee et al. [5] proposed an EPQ model with a partial backordering mechanism and decision variables based on time intervals.

Research by Lev and Weiss [6], Gascon [7], Wee et al. [8], and Yin and Kang [9] have focused on ordering policies with varying planning horizons for EPQ models. Wee and Widyadana [10] developed a production model for deteriorating items with stochastic preventive maintenance time and a rework process using the FIFO rule, while Öztürk et al. [11] proposed an EPQ-based model considering shortages, rework, and imperfect items.

Recent studies have also explored continuous-time supplier-distributor manufacturing policies (Sato et al., [12]), corporate social responsibility supply chains (Zhao et al., [13]; Xie et al., [14]), supply chain coordination with price-sensitive stochastic demand (Wang et al., [15]) and revenue and sharing policies for uncertain demand in high-tech industries during the pandemic (Huang et al., [16]).

Overall, these studies provide valuable insights into the challenges of managing production and inventory for high-tech products with decreasing demand and prices. By developing models and procedures to optimize inventory replenishment and backordering policies, these studies offer practical solutions to help high-tech industries maximize their profitability.

In their 2017 study, Shaikh et al. [17] developed an inventory model that considers non-instantaneous deterioration processes with fully backordered demand that is both price and stock dependent. Non-instantaneous deterioration occurs when the deterioration process begins after a certain period (Sana, [18]). In subsequent studies, Mashud et al. ([19], [20], [21], and [22]) and Wang et al. [15] expanded upon this model by incorporating additional factors such as different deteriorating rates, preservation technology, trade credit, and sustainable inventory management policies.

Other researchers have also explored non-instantaneous deteriorating inventory models considering various effect factors (Lee [23], Raza and Faisal, [24], Buisman et al., [25], Chung, [26], Modak and Kelle, [27], and Becerra et al., [28]). Kazemi et al. [29] applied a genetic algorithm to develop an integrated production-distribution scheduling model, while Pooya et al. [30] proposed a systematic approach to determine the most appropriate lot-sizing policies in a material requirement planning system Aazami and Saidi-Mehrabad [31] proposed a mathematical model that integrated perishable products, time-varying demand, production capacity, and transportation constraints. Sarkar and Giri [32] proposed a mathematical model to optimize the supplier’s finite production capacity and retailer's ordering policy under uncertain demand and variable backorder cost. Khorshidvand et al. [33] developed a closed-loop supply chain network design to maximize profit and minimize CO2 emission under uncertain demand. They proposed a new hybrid method using Lagrangian relaxation algorithm to solve a multi-objective nonlinear programming (NLP) model. AlAlaween et al. [34] proposed an artificial neural network to forecast the uncertainty of the demand and price in the hybrid electric cars’ spare parts.

In November 2019, pneumonia of unknown cause broke out in Wuhan, China, and a new coronavirus emerged. In just over one year. The number of confirmed cases worldwide has exceeded 76 million, and the death toll is approaching 1.7 million. With the spread of the pandemics, global demand freezes sharply, and it affects the global economy. The uncertainty of the supply chain is aggravated by the fluctuations of price and demand. Haren and Simchi-Levi [35] in their study described the disrupted production due to the pandemics. Other authors discussed the recovery stage after the pandemics have subsided (Paul and Chowdhury, [36]; Mashud et al., [37], Jana, [38], and Pujawan and Bah, [39]).

In contrast to previous studies, this study considers declining prices and demands during the pandemics and develops an integrated production-inventory policy with different

backordering strategies using an analytical formulation and optimization approach. Based on the economic production quantity (EPQ) concept, the study presents a production-inventory strategy for products with declining demand and price during pandemics. The model is formulated mathematically, and a heuristic solution procedure is used to compare the total profits for the last-in, first-out (LIFO) and first-in, first-out (FIFO) backordering policies.
A real case numerical example (Source data comes from Yiming Industrial Co., Ltd.) is provided to illustrate the application of the model, and sensitivity analysis is conducted to highlight the differences between LIFO and FIFO policies.

Note: Yiming Industrial Co., Ltd. was established in Taipei in 1979 and is affiliated to Taizhan Group. It has R&D and production bases in Neihu, Guangzhou, Kunshan and Ho Chi Minh City. Over the past 40 years, they focus on mold development and surface treatment technology, serving well-known brand customers from the machine tool industry, automobile industry, golf head industry, and medical equipment and 3C electronic products, providing them with various nameplates and metals solutions for plastic-look trim parts. They are the important supplier for notebook computer industry.

2. Notation and Parameter Assumptions

The following assumptions are used in the model development:

(1) The component restocking rate is infinite.

(2) The demand rate declines exponentially.

(3) Component cost, production cost, and consumer purchasing price decrease in a continuous manner per unit time. The holding cost, backordering cost, and the set-up cost are assumed to be constant.

(4) The planning horizon is deterministic.

(5) The component's restocking interval and production cycle time is constant.

(6) Partial backordering is considered.

(7) In the decline stage of product life cycle, two conditions are assumed during t_i^2: either $\delta_1 \geq \delta_2$ or $\delta_1 < \delta_2 \leq 1$.

(8) LIFO and FIFO policies are considered during t_i^2.

LIFO (filled the incoming orders, then the backorders): when $\delta_1 \geq \delta_2$,

FIFO (filled the backorders, then the incoming orders): when $\delta_1 < \delta_2 \leq 1$.

The followings are the related parameters.

Parameters	Description
$\theta(t)$	Weekly demand rate, where $\theta(t) = \theta_0 exp(-\theta t)$, θ_0 is the scale parameter, and θ is the sensitivity parameter of demand.
$u(t)$	Component cost per unit, $u(t) = u_0(1-\alpha)^t$ where u_0 is the component cost per unit when *t=0* and α is the component cost's weekly decrease rate...
$\rho(t)$	Selling price per unit, $\rho(t) = \rho_0(1-\beta)^t$, where ρ_0 is the selling price per unit when *t = 0*, and β is the weekly decrease rate of the consumer purchasing price.
P	Production rate.
L	Length (in weeks) of the production planning horizon.
C_1	Set-up cost of each production cycle.
C_2	Set-up cost of each component replenishment.
H_1	Holding cost for products per unit per week.
H_2	Holding cost for component per dollar per week.
C_3	Weekly backordering cost per unit.
C_4	Unit lost sales cost, including loss of profit margin and goodwill.
t_i^1	Time length of stock-out without production during the production cycle *i*, *i*=1, 2...*J*.
t_i^2	Time length of stock-out with production during the production cycle *i*
t_i^3	Time length of positive stock with production during the production cycle *i*.
t_i^4	Time length of positive stock without production during the production cycle *i*.
δ_1	Fraction of stock-outs that will be backordered during t_i^1 time.
δ_2	Fraction of stock-outs that will be backordered during t_i^2 time.
ξ	Unit usage of component.
t_c	Component replenishment Time interval.
TP	Total profit during the planning horizon.
Decision Variables	
J	Integral number of the production cycle in the planning horizon.
K	Integral number of component replenishment in the production cycle.
T	Production cycle time or length.
η	Time percentage in every production cycle with positive inventories, defined as the level of service (i.e. $\eta = 1 - \frac{t_i^1 + t_i^2}{T}$).

3. Mathematical Model

3.1 Model development

Based on the EPQ concept, the products' and components' inventory model for production with decreasing price and demand is briefly described below. The total profits for the LIFO and FIFO backorder filling policies are compared. Figure 1 depicts a graphical representation of products' and components' inventory levels at the i^{th} production cycle which consists of four parts. In the first part at the t_i^1 time interval, shortages happen without production. In the second part at the t_i^2 time interval, production begins when shortages exist. In the third part at the t_i^3 time interval, production continues and there are positive stocks. In the last part of the t_i^4 time interval, there are positive stocks without production. The decision variables are derived to maximize the total net profit over the production planning horizon. The production cycle time is expressed as:

[Insert Figure 1]

$$T = \frac{L}{J} \tag{1}$$

In Figure 1, at the t_i^1 time period, the products' inventory level is depleted by the demand rate multiplied by the backordered fraction, δ_1. The differential equation of products' inventory level can be modeled as:

$$\frac{d}{dt} I_i^1(t) = -\delta_1 \theta(t) = -\delta_1 \theta_0 exp(-\theta \bullet t) \text{ ,} \tag{2}$$

with $I_i^1(t) = 0$ at the boundary condition and $t = (i-1)T$. The value of δ_1 is the fraction of shortages backordered, where $0 \le \delta_1 \le 1$ one can derive the inventory level as follows:

$$I_i^1(t) = -(\delta_1 \theta_0) / \theta [e^{(-\theta(i-1)T} - e^{(-\theta \bullet t)}], (i-1)T \le t \le (i-1)T + t_i^1 \text{ .} \tag{3}$$

At the t_i^2 time period, the products' inventory level is increased by the production rate and depleted by the demand rate multiplied by the backordered fraction, δ_2. The differential equation is expressed as:

$$\frac{d}{dt} I_i^2(t) = P - \delta_2 \theta(t) = P - \delta_2 \theta_0 exp(-\theta \bullet t), \tag{4}$$

with $I_i^2(t) = 0$ as the boundary condition, when $t = (i-\eta)T$. Value of δ_2 is the fraction of shortages backordered, where $0 \le \delta_2 \le 1$. One can derive the inventory level as follows:

$$I_i^2(t) = \frac{(\delta_2 \ \theta_0)}{\theta}[e^{(-\theta \bullet t)} - e^{-\theta(i-n)T}] - P[(i-\eta)T - t], (i-1)T + t_i^1 \le t \le (i-\eta)T \tag{5}$$

Subsequently, this inventory model discusses the conditional situations of the FIFO and LIFO backorder systems separately at the t_i^2 time period. For the FIFO backorder system, the first assumption is for the existing backorders to be replenished before any new demands are taken in; the second assumption is that only a fraction δ_2 of the shortage is backordered while the others are lost sales. In this case $\delta_1 \ge \delta_2$. For the LIFO backorder system, the incoming demands are calculated before the backorders. In this case, $\delta_1 < \delta_2 \le 1$.

At the t_i^3 time period, the products' inventory level is increased by the production rate and diminished by the demand rate. The differential equation of products' inventory level can be expressed as follows:

$$\frac{d}{dt} I_i^3(t) = P - \theta(t) = P - \theta_0 exp(-\theta \bullet t), \tag{6}$$

with $I_i^3(t) = 0$ as the boundary condition, and the condition $t = (i - \eta)T$. One can derive the stock level as follows:

$$I_i^3(t) = P[t - (i-\eta)T] - \frac{\theta_0}{\theta}[e^{(-\theta(i-\eta)T)} - e^{(-\theta \bullet t)}], (i-\eta)T \le t \le (i-\eta)T + t_i^3. \tag{7}$$

At the t_i^4 time period, the products' inventory level is diminished by the demand rate only. The differential equation of products' inventory level can be modeled as:

$$\frac{d}{dt} I_i^4(t) = -\theta(t) = -\theta_0 exp(-\theta \bullet t), \tag{8}$$

With $I_i^4(t) = 0$ as the boundary condition and the condition $t = iT$. One can derive the inventory level as follows:

$$I_i^4(t) = \frac{\theta_0}{\theta}[e^{(-\theta \bullet t)} - e^{(-\theta \bullet iT)}], (i-\eta)T + t_i^3 \le t \le iT. \tag{9}$$

As in Figure 1, the components' inventory level, $I_{ij}(t)$, in which the production cycle *i* and the components' replenishment cycle *j* are depleted by the production rate multiplied by the unit usage rate. The differential equation can be expressed as follows:

$$\frac{d}{dt} I_{ij}(t) = -P\xi, (i-1)T + t_i^1 + (j-1)t_c \le t \le (i-1)T + t_i^1 + jt_c, \tag{10}$$

with boundary condition, $I_{ij}(t) = 0$, and the condition $t = (i-1)T + t_i^1 + jt_c$. The component replenishment time interval t_c can be derived as follows:

$$t_c = \frac{1}{K}(t_i^2 + t_i^3). \tag{11}$$

One can derive the component inventory level as:

$$I_{ij}(t) = -P\xi\{t - [(i-1)T + t_i^1 + jt_c]\}. \tag{12}$$

For the boundary condition, $I_i^1(t) = I_i^2(t)$, and the condition $t = (i-1)T + t_i^1$, one can derive a closed form of t_i^1 as follows:

$$t_i^1 = \frac{P\theta T(1-\eta)+\delta_2\theta_0 e^{-\theta \bullet iT}(e^{\theta\eta T}-e^{\theta \bullet T})}{\theta[(\delta_1-\delta_2)\ \theta_0 e^{-\theta(i-1)T}+P]}. \tag{13}$$

For $t_i^2 = \frac{L}{J}(1-\eta) - t_i^1$, one can derive the value of t_i^2. Using the boundary condition $I_i^3(t) = I_i^4(t)$ and the condition $t = (i-\eta)T + t_i^3$, one can derive:

$$t_i^3 = \frac{\theta_0 e^{-\theta \bullet iT}(e^{\theta\eta T}-1)}{\theta \bullet P}. \tag{14}$$

From (1) through (14), one can derive the sales revenue and related costs as follows:

The product sales revenue, REV, is:

$$REV = \sum_{i=1}^{J}\left[\int_{(i-1)T}^{(i-1)T+t_i^1}\delta_1\theta(t)\rho(t)dt + \int_{(i-1)T+t_i^1}^{(i-\eta)T}\delta_2\theta(t)\rho(t)dt + \int_{(i-\eta)T}^{iT}\theta(t)\rho(t)dt\right]. \tag{15}$$

The product backordering cost, BC, at time periods t_i^1 and t_i^2 is:

$$BC = \sum_{i=1}^{J} C_3\left[-\int_{(i-1)T}^{(i-1)T+t_i^1} I_i^1(t)dt - \int_{(i-1)T+t_i^1}^{(i-\eta)T} I_i^2(t)dt\right]. \tag{16}$$

The product lost sales cost, LS, at time periods t_i^1 and t_i^2 is:

$$LS = \sum_{i=1}^{J} C_4\left[\int_{(i-1)T}^{(i-1)T+t_i^1}(1-\delta_1)\theta(t)dt + \int_{(i-1)T+t_i^1}^{(i-\eta)T}(1-\delta_2)\theta(t)dt\right]. \tag{17}$$

The product holding cost, HP, at time periods t_i^3 and t_i^4 is:

$$HP = \sum_{i=1}^{j} H_1\left[\int_{(i-\eta)T}^{(i-\eta)T+t_i^3} I_i^3(t)dt + \int_{(i-\eta)T+t_i^3}^{iT} I_i^4(t)dt\right], \tag{18}$$

where $t_i^2 = (1-\eta)T - t_i^1$.

The product set-up cost, SP, is:

$$\mathrm{SP} = JC_1. \tag{19}$$

The component purchase cost, PC, is:

$$PC = \sum_{i=1}^{J}\sum_{j=1}^{K}\left[P\xi t_c u_0 (1-\alpha)^{(i-1)T+t_i^1+(j-1)t_c} \right], \tag{20}$$

Where $t_c = \frac{1}{K}(t_i^2 + t_i^3)$.

The component holding cost, HM, is:

$$HM = \sum_{i=1}^{J}\sum_{j=1}^{K} H_2 \int_{(i-1)T+t_i^1+(j-1)t_c}^{(i-1)T+t_i^1+j\tau} \mathrm{I}_{\mathrm{m}ij}(t) u_0 (1-\alpha)^{(i-1)T+t_i^1+(j-1)t_c} dt\,. \tag{21}$$

The component set-up cost, SM, is:

$$\mathrm{SM} = JKC_2. \tag{22}$$

The total profit of the production-inventory model TP is the sales revenue minus the product and the component related costs, which includes the product backordering cost, product lost sales cost, product holding cost, product set-up cost, component purchase cost, component holding cost, and component set-up cost. The problem is to optimize the following constrained total profit function with three independent variables (*J*, *K*, and η) as follows:

$$\mathrm{Max}_{0\le\eta\le1} \;\; TP(J,K,\eta) = REV - (BC + LS + HP + SP) - (PC + HM + SM), \tag{23}$$

subject to (1), (11), (13), and (14); with positive integers *J* and *K*.

3.2 Solution Procedure

The goal of the study is to maximize the overall net profit through the formulation of a heuristic solution using the decision variables in the finite planning horizon. The heuristic solution procedure is presented as follows:

(1) Assume a set of positive integral values of (J, K).

(2) Using Maple-soft, plot the illustration of the function TP when η is between $0 \le \eta \le 1$.

(2.1) If TP is mono-increasing between $0 \le \eta \le 1$ (refer to Figure 2), set η =1 and go to (3).

(2.2) If TP is mono-decreasing between $0 \le \eta \le 1$ (refer to Figure 3), set η =0 and go to (3).

(2.3) If mono-increasing or mono-decreasing does not happen to TP (refer to Figure 4), set TP =the first derivatives of η and equate it to zero, and then calculate η. If the TP function fulfills the following condition for $0 \le \eta \le 1$, go to (3); otherwise, the solution is infeasible.

$$\frac{d^2 TP(\eta \mid J, K)}{d\eta^2} < 0 \tag{24}$$

(3) Calculate TP.

(4) For various sets of (J, K, η), from procedures (1) through (3), the optimal solution of (J^*, K^*, η^*) must simultaneously satisfy the following conditions:

$$TP(J^* - 1, K^*, \eta^*) \le TP(J^*, K^*, \eta^*) \ge TP(J^* + 1, K^*, \eta^*) \tag{25}$$

and

$$TP(J^*, K^* - 1, \eta^*) \le TP(J^*, K^*, \eta^*) \ge TP(J^*, K^* + 1, \eta^*). \tag{26}$$

[Insert Figure 2]

[Insert Figure 3]

[Insert Figure 4]

4. Numerical Results

The model can be demonstrated by the following real case numerical example. (Source data comes from Yiming Industrial Co., Ltd.) With the following parameters, δ_1=δ_2=0.95, *P*=500 units per week, *L*=78 weeks, ζ=1, C_1=$600, H_1=$0.4 per unit per week, C_3=$0.7 per unit per week, C_4=$0.75 per unit, u_0=$50, α =0.01 per week, ρ_0=$100, β =0.01 per week, θ_0=200, θ =0.01, H_2=$0.004 per dollar per week, and C_2=$200.

Using the solution procedure in Section 3, the computational result is shown in Table 1. The optimal solution is *J*=15, *K*=2, η =0.77, and TP=$366,174. Each optimal value of (t_i^1, t_i^2, t_i^3 and t_i^4) is given in Table 2. One can see that t_i^2 and t_i^3 decrease simultaneously due to decreasing demand. The various costs for the optimal solution are given in Table 3.

[Insert Table 1]

[Insert Table 2]

[Insert Table 3]

5. Comment on Sensitivity Analysis

The heuristic solution of $\{J, K, \eta\}$ is derived when one of the backordering-policies parameter sets in $\Phi = \{\delta_1,\ \delta_2,\ C_4,\ H_1\}$ is changed. The computational results are given in Tables 4-7.

Some observations are given as follows.

- Smaller values of δ_1 and δ_2 denote greater penalty costs. The service levels and the number of production cycles have to be increased to reduce the penalty cost when the values of δ_1 and δ_2 decrease (Table 4). In a monopolistic market, the service level (η) might remain low because all backorders will be filled (i.e. δ_1=δ_2=1). In an imperfectly competitive market, the higher value of service-level should be maintained in order to decrease the loss in penalty cost. This is because partial backorders will benefit other competitors (i.e. δ_1<1 and δ_2<1).

- When the unit cost of lost sales increases, the service level rises to thwart the penalty cost (refer to Table 6).
- Service levels decrease to reduce inventory levels when product holding cost increases (Table 7). For example, in order to reduce the holding cost, the service level in a large-scale furniture market is kept low.
- *The sensitivity of PPI to all parameters is ranked as follows:* (refer to Table 8)
  P, θ: -30% to 30%
  ρ_0: -18% to 18%
  u_0, β: 3% to -6%
  α, θ_0: -4% to 5%
  C_1, C_2: 1% to -1%
  δ_1, δ_2*: -1% ~ 2%*
  C_3, C_4, H_1, H_2: 0.003% to -0.003%
- Following observations are made (refer to Table 9). (i) When $0 \leq \delta_1 \leq 0.92$, the total profit for the LIFO case is equal to that of the FIFO case due to an identical optimal solution when J =20, K =1, η =1. (ii) When δ_1=1, the total profit for the LIFO case is equal to that of the FIFO case due to an identical optimal solution when J =10, K =4, η =0.32. (iii) When $0.93 \leq \delta_1 \leq 0.99$, the total profit for the LIFO case is greater than that of the FIFO case due to the smaller service level. (iv) When $0.93 \leq \delta_1 \leq 0.99$, the percentage of total profit difference between the LIFO case and the FIFO case varies from 0.14% to 0.59%.
- When δ_1 ranges from 93% to 99%, it is obvious that the LIFO policy is better; otherwise, one may adopt the FIFO policy when fairness and freshness are the main priorities. This provides insight for managers to decide whether to use the LIFO or the FIFO policies (Figure 5).

[Insert Table 4]

[Insert Table 5]

[Insert Table 6]

[Insert Table 7]

[Insert Table 8]

[Insert Table 9]

[Insert Figure 5]

6. Summary and Conclusions

This study presents a production-inventory model for hi-tech industries that offer 3C products that experience rapid obsolescence. The partial backordering model takes into account the decreasing price and demand rate during pandemics. The model is derived using constrained nonlinear differential equations, and sensitivity analysis is performed for varying parameters. The study reveals that increasing the number of production cycles leads to higher service-level which needs to be increased to counteract the loss of penalty cost. The main contribution of the article is to develop a partial backordering production-inventory model for hi-tech industries that accounts for the decreasing price and demand rate during pandemics. The study provides significant insights for managerial decision-making. Decreasing service-level reduces the inventory levels when product holding cost increases. Moreover, adopting a LIFO or FIFO backordering policy depends on the backordering rate and the priority of service or profit. It is noted that LIFO is preferred when the backordering rate is above 0.92, while FIFO is preferred below 0.92. The decision making for various backordering rates are given in Table 10.

[Insert Table 10]

The study provides managerial insights to help high-tech enterprise in decision-making during the pandemics. The backordering rate can help to identify whether profit or fairness is the first priority. That is, a higher backordering rate signifies a better service–level. While the research is limited to deterministic model, future research should investigate stochastic model as well as considering other criteria such as carbon emissions and multi-products.

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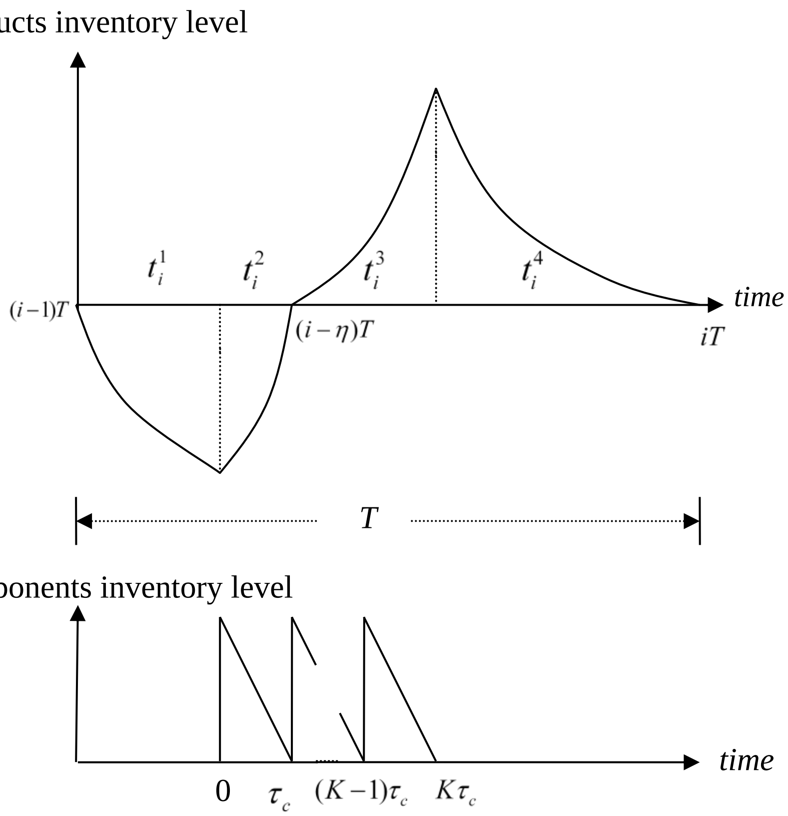

Figure 1. Products and components inventory levels in the production cycle *i*

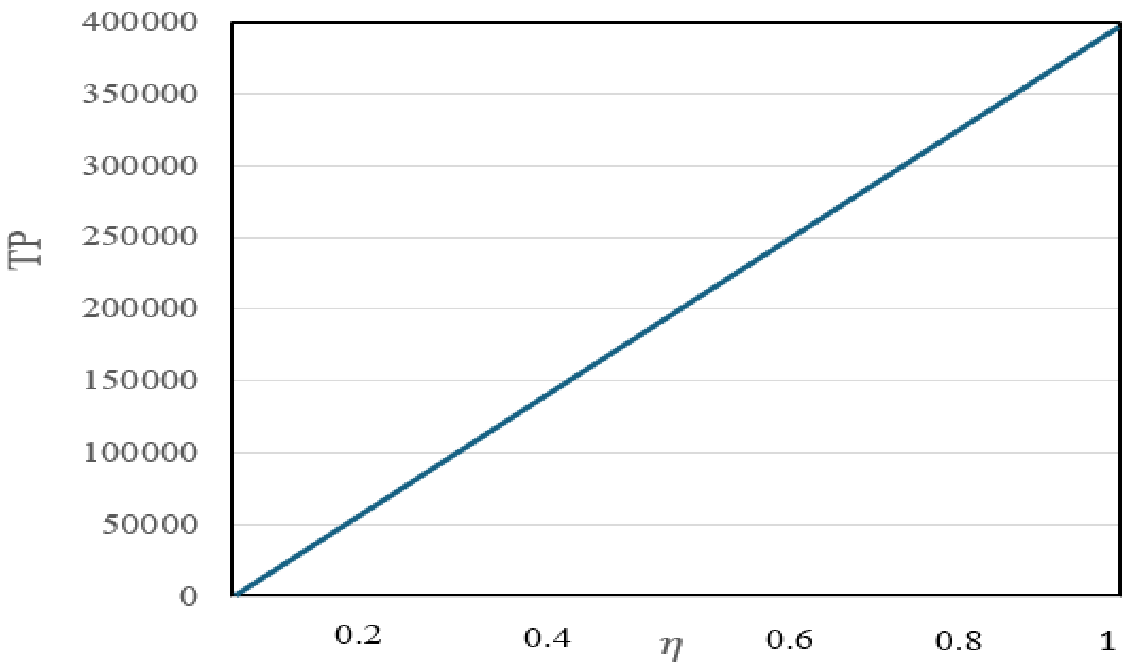

Figure 2. *TP* is mono-increasing vs. η in the feasible range $0 \le \eta \le 1$

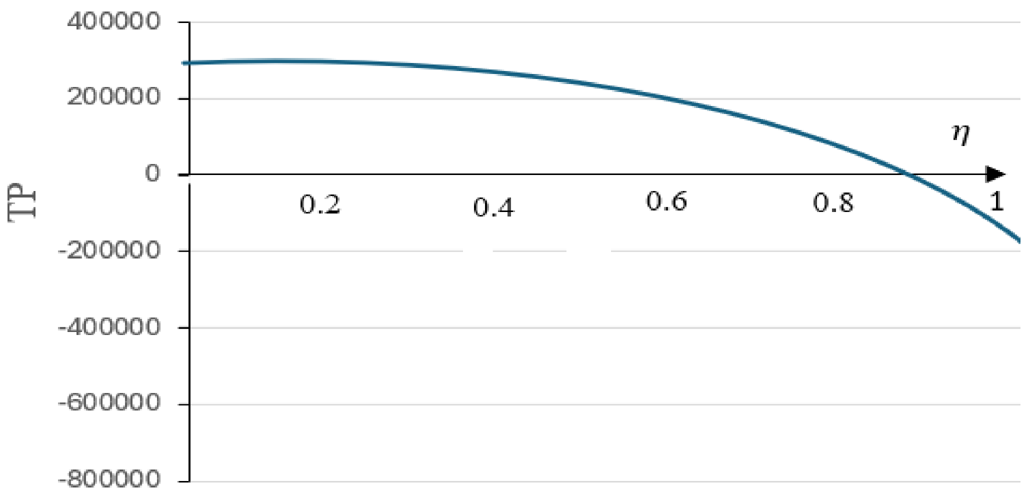

Figure 3. *TP* is mono-decreasing vs. η in the feasible range $0 \le \eta \le 1$

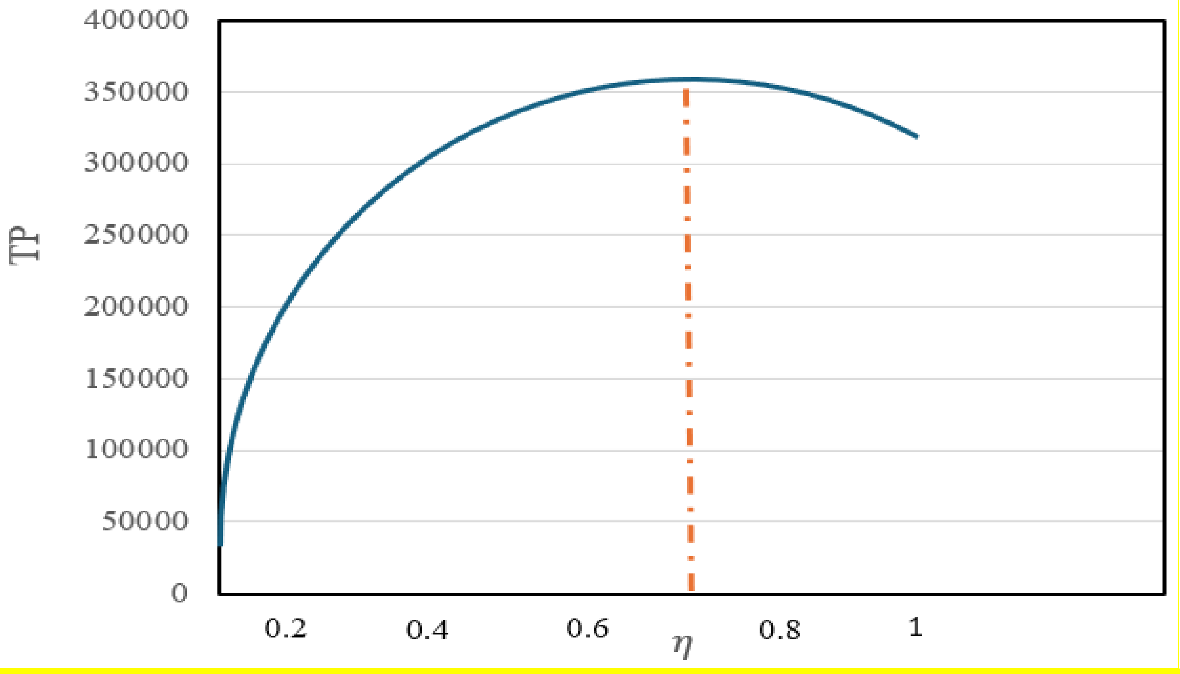

Figure 4. *TP* is neither mono-increasing nor mono-decreasing in the feasible range $0 \le \eta \le 1$

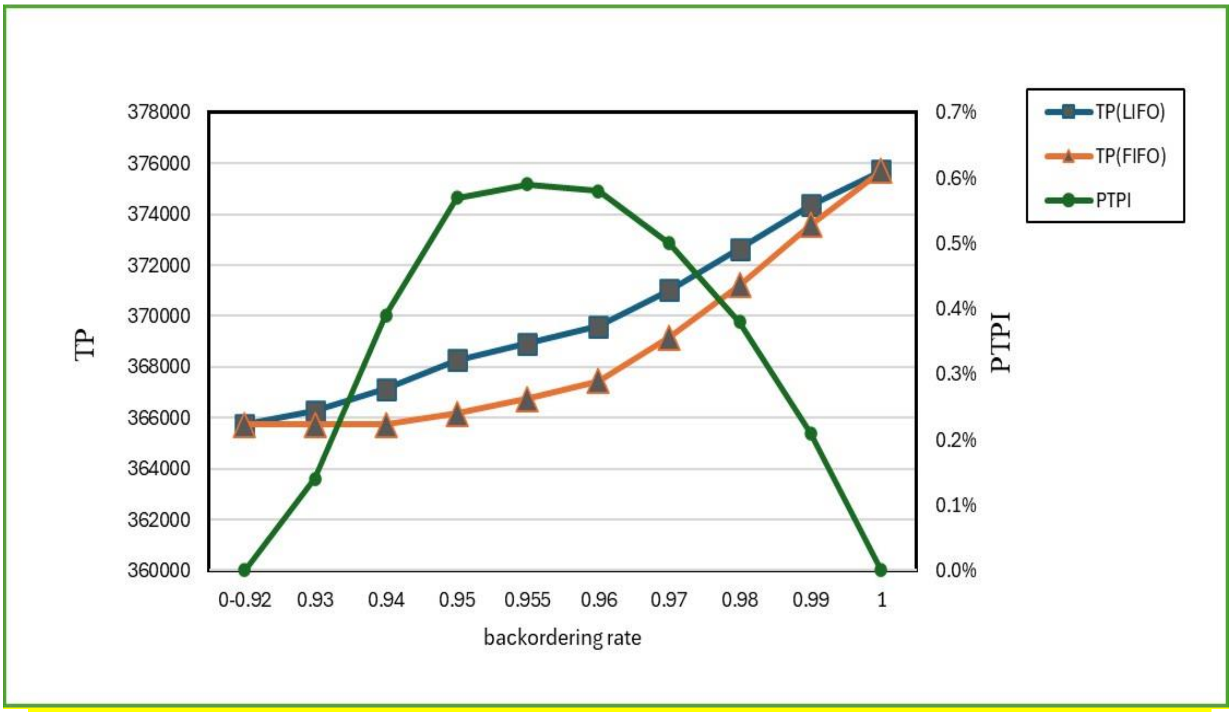

Figure 5. *TP* and *PTPI* vs. backordering rates (δ_1 and δ_2) with LIFO and FIFO backordering policies

Table 1. Computational result of various values of (J, K, η , TP)

J	K	η	TP
15	1	0.77	365491
15	2	0.77	366174*
15	3	0.78	365398
14	2	0.75	366170
16	2	0.81	366118

Note: * the optimal value.

Table 2. Optimal values of (t_i^1, t_i^2, t_i^3, and t_i^4)

i	t_i^1	t_i^2	t_i^3	t_i^4
1	0.744227	0.451773	1.551295	2.452705
2	0.767119	0.428881	1.472689	2.531311
3	0.788851	0.407149	1.398066	2.605934
4	0.809481	0.386519	1.327224	2.676776
5	0.829067	0.366933	1.259973	2.744027
6	0.847660	0.348340	1.196128	2.807872
7	0.865310	0.330690	1.135519	2.868481
8	0.882067	0.313933	1.077981	2.926019
9	0.897974	0.298026	1.023359	2.980641
10	0.913076	0.282924	0.971504	3.032496
11	0.927412	0.268588	0.922277	3.081723
12	0.941021	0.254979	0.875544	3.128456
13	0.953941	0.242059	0.831179	3.172821
14	0.966207	0.229793	0.789062	3.214938
15	0.977851	0.218149	0.749080	3.254920

Table 3. Costs for the optimal solution

J	15
K	2
η	0.777
REV	779,670.5
BC	685.0
LS	92.5
HP	4,752.6
SP	9,000.0
PC	395,327.4
HM	619.7
SM	3,000.0
TP	366,174.3

Table 4. Sensitivity analysis of δ_1 and δ_2 (FIFO policy)

δ_1, δ_2	0-0.94	{0.95}	0.96	0.97	1
J	20	15	13	12	10
K	1	2	2	2	4
η	1	0.77	0.63	0.53	0.32
TP	365737	366174	367447	369167	375699
$PPI(\%)$	-0.12	0.00	0.35	0.82	2.60

Note: *PPI*: percentage profit increasing = $(TP\text{-}TP_{Default})$ / $TP_{Default}$.

Table 5. Sensitivity analysis of δ_1 and δ_2 (LIFO policy)

δ_1, δ_2	0-0.94	{0.95}	0.96	0.97	1
J	13	12	12	12	10
K	2	2	2	2	4
η	0.65	0.58	0.52	0.48	0.32
TP	367147	368267	369590	371017	375699
$PPI(\%)$	-0.30	0.00	0.36	0.75	2.02

Note: *PPI*: percentage profit increasing = $(TP\text{-}TP_{Default})$ / $TP_{Default}$.

Table 6. Sensitivity analysis of unit lost penalty cost C_4=0.75±10%, ±20%, ±30% when (δ_1=δ_2=0.95)

C_4	0.525	0.600	0.675	{0.750}	0.825	0.900	0.975
J	14	15	15	15	15	15	15
K	2	2	2	2	2	2	2
η	0.77379	0.77478	0.77576	0.77675	0.77773	0.77872	0.77971
TP	366202	366193	366179	366174	366164	366154	366145
$PPI(\%)$	0.007647	0.005189	0.001365	0	-0.00273	-0.00546	-0.00792

Note: *PPI*: percentage profit increasing = $(TP\text{-}TP_{Default})$ / $TP_{Default}$.

Table 7. Sensitivity analysis of product holding cost H_1 =0.40±10%, ±20%, ±30%

H_1	0.28	0.32	0.36	{0.40}	0.44	0.48	0.52
J	15	15	15	15	14	14	14
K	2	2	2	2	2	2	2
η	0.87	0.84	0.80	0.77	0.73	0.70	0.66
TP	367782	367201	366668	366174	365717	365300	364908
$PPI(\%)$	0.439135	0.280468	0.134909	0	-0.1248	-0.23868	-0.34574

Note: *PPI*: percentage profit increasing = $(TP\text{-}TP_{Default})$ / $TP_{Default}$.

Table 8. The sensitivity analysis of PPI

Parameter	Changed %					
	-30%	-20%	-10%	+10%	+20%	+30%
P	-29%	-19%	-9%	9%	19%	28%
C_1	1.113%	1.002%	0.723%	-0.653%	-0.855%	-1.021%
C_2	1.070%	0.972%	0.654%	-0.457%	-0.740%	-0.919%
H_1	0.430%	0.343%	0.107%	-0.094%	-0.257%	-0.340%
H_2	0.221%	0.094%	0.080%	-0.008%	-0.117%	-0.200%
C_3	0.003%	0.001%	0.000%	-0.000%	-0.001%	-0.003%
C_4	0.007%	0.001%	0.000%	-0.000%	-0.001%	-0.007%
δ_1	-1.0%	-0.4%	-0.1%	0.4%	1.0%	2.0%
δ_2	-1.0%	-0.4%	-0.1%	0.4%	1.0%	2.0%
u_0	5%	3%	2%	-2%	-3%	-5%
ρ_0	-18%	-12%	-6%	6%	12%	18%
α	-2%	-1%	-1%	1%	1%	3%
β	3%	3%	2%	-2%	-4%	-6%
θ_0	-4%	-3%	-2%	2%	3%	5%
θ	-30%	-20%	-10%	10%	21%	32%

Note: *PPI*: percentage profit increasing = $(TP\text{-}TP_{Default}) / TP_{Default}$.

Table 9. Computational result with LIFO and FIFO backordering policies

LIFO	δ_1 ($\delta_2 = 1$)	0-0.92	0.93	0.94	0.95	0.955	0.96	0.97	0.98	0.99	1
	J	20	14	13	12	12	12	12	11	11	10
	K	1	2	2	2	2	2	2	2	2	4
	η	1	0.77	0.65	0.58	0.54	0.52	0.48	0.41	0.37	0.32
	TP	365737	366261	367147	368267	368917	369590	371017	372645	374364	375699
FIFO	δ_1, δ_2 ($\delta_1 = \delta_2$)	0-0.92	0.93	0.94	0.95	0.955	0.96	0.97	0.98	0.99	1
	J	20	20	20	15	14	13	12	12	11	10
	K	1	1	1	2	2	2	2	2	2	4
	η	1	1	1	0.77	0.69	0.63	0.53	0.46	0.38	0.32
	TP	365737	365737	365737	366174	366744	367447	369165	371223	373574	375699
$PTPI$		0%	0.14%	0.39%	0.57%	0.59%	0.58%	0.50%	0.38%	0.21%	0%

Notes: TP (LIFO): Total profit in the case of the LIFO policy; TP (FIFO): Total profit in the case of the FIFO policy; percentage total profit increase (*PTPI*) is defined as

$$PTPI = \frac{TP(LIFO) - TP(FIFO)}{TP(FIFO)}$$

Table 10. Decision making for various backordering rates.

Priority consideration	$\delta_1 \leq 0.92$	$\delta_1 > 0.92$
(Scenario 1) 1st: fairness 2nd: total profit	FIFO	FIFO
(Scenario 2) 1st: total profit 2nd: fairness	FIFO	LIFO

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