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The optimal order quantity, quality investment, and specification limits settings for the production and supply model

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ABSTRACT

Supply chain is the operation of the flow of goods and services, and includes all processes that transform raw materials into final products. It involves the active streamlining of a business's supply-side activities to maximize customer value and gain a competitive advantage in the marketplace. In recent years, many researchers have proposed the integrated supply chain models with production, inspection, maintenance and quality. Chuang and Wu (2019) developed an integrated model to determine the optimum supplier's process mean and quality investment settings and retailer's number of shipment, order quantity and maximum backorder quantity with maximization of total profit of supply chain system. In the present paper, Chuang and Wu's model is modified with the constraint of the specified process capability index C_{pm} value, where the mean and standard deviation of process characteristic are assumed to be the declining exponential reduction function. The decision variables in this modified model include supplier's parameters (i.e., quality investment and specification limits) and retailer's parameters (i.e., order quantity, number of shipments and maximum backorder quantity). A numerical example is provided for illustration. Based on the sensitivity analysis, it may be seen that the supply chain's total profit is positively influenced by the production rate, the demand rate, the purchasing cost, the selling price and the quality investment, and is negatively affected by the production cost, the specified process capability index, the target value, the maximum mean and both the minimum and the maximum standard deviations of process characteristic.

Keywords: Quality investment, Specification limits, Process capability index, Order quantity, Backorder.

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1. INTRODUCTION

The economic manufacturing quantity (EMQ) model determines the quantity a manufacturer should produce to minimize the total inventory costs by balancing the inventory holding cost and average fixed ordering cost. Traditional EMQ models assume that all received items meet specifications (i.e., perfect quality). However, this assumption may not be tenable in practical situations. That is, lots received may include imperfect items and the procedures used to screen the items may have errors, such as misclassifying a good item as rework, good item as scrap, rework item as good, and so on. The imperfect EMQ model was firstly considered by Porteus (1986); Rosenblatt and Lee (1986a; 1986b) to minimize the total expected cost, including the quality cost, set-up cost and holding cost of products per unit time, in which the manufacturer may have defective items in the production process and these defective items usually result in internal or external failure quality cost.

Recently, many researchers have proposed the integrated EMQ model with production, inspection, maintenance, and quality. For example, Darwish (2009) developed a single-vendor single-buyer supply chain model for determining the optimal process mean, production lot size and number of shipment of products to buyer. Subsequently, Chen and Tsai (2016) modified Darwish's model (2009) with product quality loss for minimizing the expected total relevant cost of products per unit time. Sana (2010a; 2010b) further proposed a production-inventory model with an imperfect production system for defective items restored to their original quality by rework. Lately, Sana (2016) developed a production-inventory model of a two-stage supply chain, consisting of one manufacturer and one retailer, to study production lot size/order quantity, reorder point sales teams' initiatives where demand of the end customers was dependent on random variable and sales teams' initiatives simultaneously.

Saxena et al. (2017) presented a green supply chain inventory model for integrated production of new items and remanufacturing of redeemable returned items under a situation in which the vendor provided the buyer with a permissible delay of payments and supplied the serviceable items to the buyer on lot-for-lot basis. Modak et al. (2018) introduced a manufacturer–retailer supply chain model where cost of greenhouse gas emission during manufacturing process was taken into account. Chuany and Wu (2019) addressed an integrated model with supplier's process mean and quality investment settings and retailer's number of shipment, order quantity and maximal backorder quantity.

Bhattacharyya and Sana (2019) proposed a mathematical model of production inventory system of green products in a green manufacturing industry. Salas-Navarro et al. (2019) proposed an economic production quantity (EPQ) inventory model considering imperfect items and probabilistic demand for a two-echelon supply chain. Taleizadeh et al. (2019) formulated two multi-product single-machine EPQ models by considering imperfect products. Akhyani et al. (2020) presented a new method for customer classification based on the satisfaction with services in the insurance company. Taleizade et al. (2020) dealt with optimal pricing and production tactics for a bi-echelon green supply chain, including a producer and a vendor in presence of three various scenarios, in which demand was assumed to be dependent on a price, refund and quality where the producer controlled quality and the vendor proposed a refund policy to purchasers to encourage them to order more.

Taguchi (1986) redefined the product quality as society loss when products were shipped to customers. He proposed the quadratic quality loss function for measuring the product quality, where the product with minimum bias and variability had the optimum quality. Taguchi's quadratic quality loss function (1986) is able to promote the probability of output product with optimum target value and has been successfully applied in various areas of on-line and off-line quality control.

Process capability index is usually used for examining if a production or service process is capable. Chan et al. (1988) developed the index C_{pm} in order to take into account the process centering. Boyles (1991) pointed out that the index C_{pm} was identical to the indicator proposed by Taguchi (1986). Pearn et al. (1992) introduced another process capability index C_{pmk} which considered the difference between process mean and specification center. Jeang (2010) proposed a modified C_{pm} index by considering the balance between tolerance cost and quality loss applied in the real production process. For the off-line and on-line quality control, process optimization is emphasized by obtaining the minimum expected total loss of society including producers and customers. The modern manufacturing process usually requires very low parts per million (PPM) fraction of defectives. By setting the specified C_{pm} value for the process, the output product with the constrained loss of customer may be assured.

The setting of economic specification limits is considered a short-term method for quality assurance when products are shipped to customers. The quality investment is an alternative long-term approach for improving the process parameters. Examples of quality investment include adoption of the new machine equipment, the new software system, the new manufacturing method, the new tools, and the personal education training for improving the production process. Hong et al. (1993), Ganeshan et al. (2001), Chen and Tsou (2003), and Tsou (2006) employed the declining exponential reduction of process mean and standard deviation as the function of quality investment. Chuang and Wu (2019) applied the quality investment function with declining exponential reduction of process variability for formulating the supply chain model with optimal supplier's process mean and quality investment and retailer's number of shipments, order quantity and maximum backorder quantity. Chuang and Wu (2018) further considered the two-part trade credit policy with quality loss for determining the supplier's process mean and quality investment and retailer's order quantity, number of shipments and the length of replenishment cycle with maximization of total supply chain profit.

Although process capability index, process mean setting, economic specification limits setting and quality investment are four different methods in statistical quality control (SQC), these methods may be integrated for quality assurance and improvement such that the quality performance of products or service can be significantly promoted. In the present paper, Chuang and Wu's model (2019) is modified with specified process capability index C_{pm} value for determining the supplier's quality investment and product's specification limits, and retailer's order quantity, number of shipments and maximum backorder quantity. The major difference of our modified model and the original Chuang and Wu's model (2019) is that the former addresses that the quality investment may improve process bias and variability, that the specified process capability index C_{pm} value may assure the constrained loss for customers, and that the maximum total profit of supply chain system could be obtained under customer's satisfaction. In the next section, Chuang and Wu's model (2019) is briefly reviewed. And then, our modified model, as well as its solution procedure, is developed. A numerical example is subsequently given for illustration and the sensitivity analysis is conducted to investigate the effects of model parameters on the optimum solution of the model. Finally, some concluding remarks are drawn based on the results of sensitivity analysis.

2. CHUANG AND WU'S MODEL

Chuang and Wu (2019) proposed an integrated supplier-retailer supply chain model considering the optimal process mean setting and quality improvement under asymmetrical tolerance design, lot shipment and allowable shortage. The supplier's total profit in a production cycle is the sales revenue subtracted by the production cost, set-up cost, holding cost, rework cost, and scrap cost and the expected quality loss and quality investment. The retailer's total profit in a replenishment cycle is the sales revenue subtracted by the purchasing cost, ordering cost, holding cost, backorder penalty and shipping cost. The supply chain's total profit function is composed of both the supplier's and the retailer's total profit functions. In Chuang and Wu's model (2019), the supplier's process mean and quality investment and retailer's order quantity, number of shipments, and maximum backorder quantity are the decision variables to be determined. From Chuang and Wu (2019), the production and supply model is formulated as follows:

P is the annual production rate; K is the setup cost per setup; Ps is the production cost per item; h_s is the holding cost per item per year; I is the quality investment; σ_{min}^2 is the minimum variance of process characteristic; σ_{max}^2 is the maximum variance of process characteristic; σ_I^2 is the improved variance of process characteristic; LSL is the lower specification limit of process characteristic; USL is the upper specification limit of process characteristic; T is the target value of process characteristic; μ is the mean of process characteristic; C_U is the rework cost when the value of process characteristic is greater than USL; C_L is the scrap cost when the value of process characteristic is less than LSL; k_L and k_U are coefficients of the quality loss function when the value of process characteristic is below T or above T, respectively; $TP_S(\mu, I)$ is the supplier's total profit function; D is the annual demand rate; A is the ordering cost per order; S is the shipping cost per shipment; P_R is the purchasing cost per item; S_R is the selling price per item; h_R is the holding cost per item; b_R is the backorder cost per item per year; B is the maximum backorder quantity; Q is the retailer's order quantity; n is the number of shipments from supplier to retailer in a production cycle; $TP_R(n, Q(n,\mu,I), B(Q(n,u,I)))$ is the retailer's total profit function; r is the rework failure rate; $TP(n,\mu,I,Q(n,\mu,I),B(Q(n,\mu,I))$ is the supply chain's total profit function.

In Chuang and Wu's supply chain model (2019), the decision variables to be determined include supplier's process mean and quality investment and retailer's order quantity, number of shipments and maximum backorder quantity.

Maximize

$$TP(n,\mu,I,Q(n,\mu,I),B\big(Q(n,\mu,I)\big)) = TP_S(\mu,I) + TP_R(n,Q(n,\mu,I),\mathrm{B}(Q(n,\mu,I)) \tag{1}$$

where $Q(n,\mu,I) = \sqrt{\dfrac{D(k+I+A+nS)}{h_S D\left[\frac{(\frac{1}{n}-\frac{1}{2})}{P[1-P_L(\mu,I)-rP_U(\mu,I)]}+\frac{n-1}{2nD}\right]+\frac{h_R b_R}{2n(h_R+b_R)}}}$;

$B(Q(n,\mu,I)) = \dfrac{h_R}{h_R+b_R}\,Q(n,\mu,I)$; $\sigma_I^2 = \sigma_{min}^2 + (\sigma_{max}^2 - \sigma_{min}^2)\,e^{-bI}$; $P_L(\mu,I) = \dfrac{1}{\sigma_I\sqrt{2\pi}}\displaystyle\int_{-\infty}^{LSL} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma_I}\right)^2}dx$;

$P_U(\mu,I) = \dfrac{1}{\sigma_I\sqrt{2\pi}}\displaystyle\int_{USL}^{\infty} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma_I}\right)^2}dx$;

$$\begin{aligned} TP_S(\mu,I) = {} & DP_R - \frac{DP_s}{[1-P_L(\mu,I)-rP_U(\mu,I)]} - \frac{DK}{Q} - h_S DQ\left[\frac{\left(\frac{1}{n}-\frac{1}{2}\right)}{P[1-P_L(\mu,I)-rP_U(\mu,I)]}+\frac{n-1}{2nD}\right] \\ & - \frac{DC_U P_U(\mu,I)}{[1-P_L(\mu,I)-rP_U(\mu,I)]} - \frac{DC_L[P_L(\mu,I)+rP_U(\mu,I)]}{[1-P_L(\mu,I)-rP_U(\mu,I)]} \\ & - D\left[\int_{LSL}^{T}\frac{k_L(x-T)^2}{\sigma_I\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma_I}\right)^2}dx + \int_{T}^{USL}\frac{k_U(x-T)^2}{\sigma_I\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma_I}\right)^2}dx\right] - \frac{DI}{Q}; \end{aligned}$$

$$TP_R(n,Q(n,\mu,I),B\big(Q(n,u,I)\big)) = DS_R - DP_R - \frac{DA}{Q} - \frac{h_R(Q-B)^2}{2nQ} - \frac{b_R B^2}{2nQ} - \frac{nDS}{Q};$$

3. MODIFIED MODEL

In addition to the similar notations in Chuang and Wu's supply chain model (2019), the additional notations in our modified model are as follows: K_m is the specified process capability index C_{pm} value; a is the coefficient of lower specification limit of process characteristic; b is the coefficient of upper specification limit of process characteristic; d is times of improved standard deviation of process characteristic for the bias; μ_I is the improved mean of process characteristic; m is the specification center of process characteristic; T is the target value of process characteristic. In our modified model, the supply chain's total profit function $TP(n,I,a,b,Q(n,I),B(Q(n,I)))$ includes both the supplier's total profit function $TP_s(I,a,b)$ and the retailer's total profit function $TP_R(n,Q(n,I),B\big(Q(n,I)\big))$. The components in supplier's total profit function include the sales revenue, the production cost, the setup cost, the holding cost, the rework cost, the scrap cost, the expected quality loss and the quality investment. The components in retailer's total profit function include the sales revenue, the purchasing cost, the ordering cost, the holding cost, the backorder penalty cost and the shipping cost. The modified model is to

$$\text{maximize } TP(n,I,a,b,Q(n,I),B(Q(n,I))) \tag{2}$$

$$\text{subject to } C_{pm}=K_m \tag{3}$$

where $Q(n,I)=\sqrt{\dfrac{D(k+I+A+nS)}{h_s D\left[\frac{(\frac{1}{n}-\frac{1}{2})}{P[1-P_L(I)-rP_U(I)]}+\frac{n-1}{2nD}\right]+\frac{h_R b_R}{2n(h_R+b_R)}}}$; $B(Q(n,I))=\dfrac{h_R}{h_R+b_R}\;Q(n,I)$;

$$\begin{cases} LSL=\mu_I-a\sigma_I \\ USL=\mu_I+b\sigma_I \end{cases};\quad m=\frac{LSL+USL}{2};\quad |m-T|=d\sigma_I;$$

$$\begin{aligned} TP_s(I,a,b)=\;&DP_R-\frac{DP_s}{[1-P_L(I)-rP_U(I)]}-\frac{DK}{Q}-h_sDQ\left[\frac{(\frac{1}{n}-\frac{1}{2})}{P[1-P_L(I)-rP_U(I)]}+\frac{n-1}{2nD}\right]\\ &-\frac{DC_UP_U(I)}{[1-P_L(I)-rP_U(I)]}-\frac{DC_L[P_L(I)+rP_U(I)]}{[1-P_L(I)-rP_U(I)]}\\ &-D\left[\int_{LSL}^{T}\frac{k_L(x-T)^2}{\sigma_I\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{x-\mu_I}{\sigma_I}\right)^2}dx+\int_{T}^{USL}\frac{k_U(x-T)^2}{\sigma_I\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{x-\mu_I}{\sigma_I}\right)^2}dx\right]-\frac{DI}{Q}; \end{aligned}$$

$$TP_R\big(n,Q(n,I),B\big(Q(n,I)\big)\big)=DS_R-DP_R-\frac{DA}{Q}-\frac{h_R(Q-B)^2}{2nQ}-\frac{b_RB^2}{2nQ}-\frac{nDS}{Q};$$

$$\begin{aligned} &\int_{LSL}^{T}\frac{k_L(x-T)^2}{\sigma_I\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{x-\mu_I}{\sigma_I}\right)^2}dx\\ &=k_L\left\{(\sigma_I^2+\mu_I^2)\Phi\left(\frac{T-\mu_I}{\sigma_I}\right)-\sigma_I(T+\mu_I)\phi\left(\frac{T-\mu_I}{\sigma_I}\right)-(\sigma_I^2+\mu_I^2)\Phi\left(\frac{LSL-\mu_I}{\sigma_I}\right)\right.\\ &\quad+\sigma_I(LSL+\mu_I)\phi\left(\frac{LSL-\mu_I}{\sigma_I}\right)-2T\left[-\sigma_I\phi\left(\frac{T-\mu_I}{\sigma_I}\right)+\mu_I\Phi\left(\frac{T-\mu_I}{\sigma_I}\right)+\sigma_I\phi\left(\frac{LSL-\mu_I}{\sigma_I}\right)\right.\\ &\quad\left.\left.-\mu_I\Phi\left(\frac{LSL-\mu_I}{\sigma_I}\right)\right]+T^2\left[\Phi\left(\frac{T-\mu_I}{\sigma_I}\right)-\Phi\left(\frac{LSL-\mu_I}{\sigma_I}\right)\right]\right\}; \end{aligned}$$

$$\begin{aligned} &\int_{T}^{USL}\frac{k_U(x-T)^2}{\sigma_I\sqrt{2\pi}}e^{-\frac{1}{2}\left(\frac{x-\mu_I}{\sigma_I}\right)^2}dx\\ &=k_U\left\{(\sigma_I^2+\mu_I^2)\Phi\left(\frac{USL-\mu_I}{\sigma_I}\right)-\sigma_I(USL+\mu_I)\phi\left(\frac{USL-\mu_I}{\sigma_I}\right)\right.\\ &\quad-(\sigma_I^2+\mu_I^2)\Phi\left(\frac{T-\mu_I}{\sigma_I}\right)+\sigma_I(T+\mu_I)\phi\left(\frac{T-\mu_I}{\sigma_I}\right)\\ &\quad-2T\left[-\sigma_I\phi\left(\frac{USL-\mu_I}{\sigma_I}\right)+\mu_I\Phi\left(\frac{USL-\mu_I}{\sigma_I}\right)+\sigma_I\phi\left(\frac{T-\mu_I}{\sigma_I}\right)-\mu_I\Phi\left(\frac{T-\mu_I}{\sigma_I}\right)\right]\\ &\quad\left.+T^2\left[\Phi\left(\frac{USL-\mu_I}{\sigma_I}\right)-\Phi\left(\frac{T-\mu_I}{\sigma_I}\right)\right]\right\};\quad \mu_I^2=\mu_{min}^2+(\mu_{max}^2\text{-}\mu_{min}^2)e^{-\beta I}; \end{aligned}$$

$\sigma_I^2=\sigma_{min}^2+(\sigma_{max}^2\text{-}\sigma_{min}^2)e^{-\alpha I}$; $P_L(I)=\dfrac{1}{\sigma_I\sqrt{2\pi}}\int_{-\infty}^{LSL}e^{-\frac{1}{2}\left(\frac{x-\mu_I}{\sigma_I}\right)^2}dx$; $P_U(I)=\dfrac{1}{\sigma_I\sqrt{2\pi}}\int_{USL}^{\infty}e^{-\frac{1}{2}\left(\frac{x-\mu_I}{\sigma_I}\right)^2}dx$;

$$k_L=\frac{C_L}{(T-LSL)^2};\quad k_U=\frac{C_U}{(USL-T)^2}.$$

In order to meet the constraint condition in Equation (3), the combination (a, b) can be obtained by considering the following two cases:

Case 1. $m \geq T$, $C_{pm} = \frac{a+b}{6\sqrt{1+\left[\frac{(b-a)}{2}+d\right]^2}}$

and consequently $t_1 a^2 + t_2 a + t_3 = 0$

where $t_1 = 1 - 9K_m^2$

$t_2 = 2b + 18bK_m^2 + 36dK_m^2$

$t_3 = b^2 - 9K_m^2(b^2 + 4 + 4bd + 4d^2)$

if $K_m \neq \frac{1}{3}, a = \frac{-t_2 \pm \sqrt{t_2^2 - 4t_1 t_3}}{2t_1}, t_2^2 - 4t_1 t_3 > 0$

Case 2. $m < T, C_{pm} = \frac{a+b}{6\sqrt{1+\left[\frac{(b-a)}{2}-d\right]^2}}$

and then $t_1 a^2 + t_2 a + t_3 = 0$

where $t_1 = 1 - 9K_m^2$

$t_2 = 2b + 18bK_m^2 - 36dK_m^2$

$t_3 = b^2 - 9K_m^2(b^2 + 4 - 4bd + 4d^2)$

if $K_m \neq \frac{1}{3}, a = \frac{-t_2 \pm \sqrt{t_2^2 - 4t_1 t_3}}{2t_1}, t_2^2 - 4t_1 t_3 > 0$

Hence, all combinations (a, b) may be obtained to satisfy Case 1 or Case 2 for the specified C_{pm} value. Then the optimum integer values of n and I and corresponding $Q(n, I)$ and $B(Q(n, I))$ can be determined with maximization of total profit of supply chain system. The solution procedure for our modified model in Equations (2)-(3) is described as follows:

Step 1. Give the specified C_{pm} value, i.e., K_m .

Step 2. Set the scope of all possible b value, where $0 < b < b_{max}$.

Step 3.(i) Adopt the approach given in Chen et al. (2014, p. 201) for obtaining the combination (a, b) satisfying Equation (3).

(ii) For a given b, the corresponding a is calculated to meet the required condition.

(iii) For $|m - T| = d\sigma_I$, substitute the feasible integer values of n and I into Equation (2) and compute the corresponding $Q(n, I)$, $B(Q(n, I))$ and $TP(n, I, a, b, Q(n, I), B(Q(n, I)))$.

(iv) Let $b = b + 0.01$. Repeat (ii) and (iii) until $b = b_{max}$.

Step 4. The combination $(n, I, a, b, Q(n, I), B(Q(n, I)))$ with maximum $TP(n, I, a, b, Q(n, I), B(Q(n, I)))$ is the optimum solution.

4. NUMERICAL EXAMPLE AND SENSITIVITY ANALYSIS OF PARAMETERS

Based on the same numerical example presented in Chuang and Wu (2019), additional parameters related to quality improvement are set as follows:

- The specified process capability index C_{pm} value, i.e., $K_m = 1$;
- The target value of process characteristic is $T = 402$;
- The minimum mean of process characteristic is $\mu_{min} = 402$;
- The maximum mean of process characteristic is $\mu_{max} = 402.86$;
- The minimum standard deviation of process characteristic is $\sigma_{min} = 0$;
- The maximum standard deviation of process characteristic is $\sigma_{max} = 0.66$;
- The quality investment constant for the standard deviation of process characteristic is $\alpha = 0.01$;
- The quality investment constant for the mean of process characteristic is $\beta = 0.05$;
- The rework failure rate is $r = 0.01$;
- The times of improved standard deviation of process characteristic for bias is $d = 0.2$;
- The coefficient of lower specification limit of process characteristic is a;
- The coefficient of upper specification limit of process characteristic is b;
- The quality investment is I.

Meanwhile, the cost settings in a supply chain model are as follows:

1. Supplier: The production rate is $P = 1500$ units/year;
   The production cost is $P_s = 30$/unit;
   The set-up cost is $K = 750$/set-up;
   The holding cost is $h_s = 12$/unit/year;
   The rework cost is $C_U = 50$/unit;
   The scrap cost is $C_L = 70$.
2. Retailer: The demand rate is $D = 1200$units/year;
   The purchasing cost is $P_R = 42$/unit;
   The selling price is $S_R = 60$/unit;
   The ordering cost is $A = 130$/order;
   The holding cost is $h_R = 16$/unit/year;
   The shipping cost is $S = 500$/ship;
   The backorder cost is $b_R = 64$/unit/year.

By solving the modified model in Equations (2)-(3), we have $n = 4$ and $I = 183$ with corresponding $Q(n, I) = 1000$, $B(Q(n, I)) = 200$, $\mu_I = 402.00$, $\sigma_I = 0.2643$, $a = 3.164$, $b = 2.840$, $LSL = 401.164$, $USL = 402.751$, $TP_S(I, a, b) = 9904.112$,

$TP_R(n, Q(n, I), B(Q(n, I))) = 17444.22$, and

$TP(n. I, a, b, Q(n, I), B(Q(n, I))) = 27348.33$.

Table 1 shows the sensitivity analysis of some model parameters. From Table l, the following phenomena may be observed:

1. As the production rate P increases from 1300 to 2500, there are the following major effects: (1) the retailer's order quantity decreases; (2) the maximum backorder quantity decreases; (3) the number of shipment decreases; (4) the supplier's total profit decreases; (5) the supply chain's total profit increases.

Table 1. Sensitivity analysis for some model parameters

P	Q	B	I	n	a	b	TP_S	TP_R	TP
1300	1631	326	183	7	3.164	2.840	10504.97	17438.13	27943.1
2250	632	126	183	2	3.164	2.840	9454.51	17432.01	26886.52
P_S	Q	B	I	n	a	b	TP_S	TP_R	TP
15	1000	200	183	4	3.164	2.840	27918.59	17444.22	45362.81
45	1000	200	183	4	3.164	2.840	-8110.36	17444.22	9333.86

Notes: $TP_S = TP_S(I,a,b)$; $TP_R = TP_R(n.Q(n,I),B(Q(n,I))$; $Q = Q(n,I)$; $B = B(Q(n,I))$; $TP = TP(n,I,a,b,Q(n,I),B(Q(n,I)))$

Table 1. (Continued)

K	Q	B	I	n	a	b	TP_S	TP_R	TP
375	763	153	183	3	3.164	2.840	10414.82	17408.09	27822.91
900	1186	237	183	5	3.164	2.840	9752.04	17420.69	27172.73
h_s	Q	B	I	n	a	b	TP_S	TP_R	TP
6	1386	277	183	5	3.164	2.840	10985.1	17549.02	28534.12
18	883	177	183	4	3.164	2.840	9074.63	17293.04	26367.67

Notes: $TP_S = TP_S(I,a,b)$; $TP_R = TP_R(n.Q(n,I),B(Q(n,I))$; $Q = Q(n,I)$; $B = B(Q(n,I))$; $TP = TP(n,I,a,b,Q(n,I),B(Q(n,I)))$

Table 1. (Continued)

D	Q	B	I	n	a	b	TP_S	TP_R	TP
600	447	89	183	2	3.164	2.840	3967.69	7852.79	11820.48
1300	1258	252	183	5	3.164	2.840	11140.93	19072.1	30213.03
P_R	Q	B	I	n	a	b	TP_S	TP_R	TP
21	1000	200	183	4	3.164	2.840	-15295.89	42644.22	27348.33
63	1000	200	183	4	3.164	2.840	35104.11	-7755.78	27348.33
S_R	Q	B	I	n	a	b	TP_S	TP_R	TP
48	1000	200	183	4	3.164	2.840	9904.11	3044.22	12948.33
90	1000	200	183	4	3.164	2.840	9904.11	53444.22	63348.33

Notes: $TP_S = TP_S(I,a,b)$; $TP_R = TP_R(n.Q(n,I),B(Q(n,I))$; $Q = Q(n,I)$; $B = B(Q(n,I))$; $TP = TP(n,I,a,b,Q(n,I),B(Q(n,I)))$

Table 1. (Continued)

K_m	Q	B	I	n	a	b	TP_S	TP_R	TP
0.5	1005	201	190	4	2.237	0.940	21358.56	17448.55	38807.06
1.2	1000	200	183	4	3.776	3.970	10317.83	17444.00	27761.83
T	Q	B	I	n	a	b	TP_S	TP_R	TP
398	973	195	190	4	3.143	3.040	9334493	17416.39	9351909
404	1000	200	186	4	3.171	3.660	11078.61	17444.69	28523.30
μ_{max}	Q	B	I	n	a	b	TP_S	TP_R	TP
401	1000	200	183	4	3.130	3.310	11660.49	17444.26	29104.75
404	1000	200	183	4	3.130	3.30	9743.99	17444.26	27188.25
σ_{min}	Q	B	I	n	a	b	TP_S	TP_R	TP
0.1	1001	200	191	4	3.658	2.540	10118.83	17445.25	27564.07
0.4	988	198	108	4	3.217	3.880	6726.74	17432.03	24158.77

Notes: $TP_S = TP_S(I,a,b)$; $TP_R = TP_R(n.Q(n,I),B(Q(n,I))$; $Q = Q(n,I)$; $B = B(Q(n,I))$; $TP = TP(n,I,a,b,Q(n,I),B(Q(n,I)))$

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Table 1. (Continued)

σ_{max}	Q	B	I	n	a	b	TP_S	TP_R	TP
0.4	1003	201	200	4	3.406	2.620	25536.98	17446.70	42983.68
0.8	1001	200	187	4	3.154	2.980	8316.83	17444.86	25761.69
α	Q	B	I	n	a	b	TP_S	TP_R	TP
0.02	1001	200	192	4	3.658	2.540	39345.01	17445.4	56790.41
0.04	1003	201	200	4	3.557	2.560	2330531	17446.65	234797.80
β	Q	B	I	n	a	b	TP_S	TP_R	TP
0.02	1001	200	185	4	3.160	3.590	10058.18	17444.54	27502.72
0.09	1000	200	183	4	3.130	3.310	11660.49	17444.26	29104.75

Notes: $TP_S = TP_S(I, a, b)$; $TP_R = TP_R(n. Q(n, I), B(Q(n, I))$; $Q = Q(n, I)$; $B = B(Q(n, I))$; $TP = TP(n, I, a, b, Q(n, I), B(Q(n, I)))$

2. As the production cost P_s increases from 15 to 45, there are the following major effects: (1) the supplier's total profit decreases; (2) the supply chain's total profit decreases.
3. As the set-up cost K increases from 375 to 900, there are the following major effects: (1) the retailer's order quantity increases; (2) the maximum backorder quantity increases; (3) the number of shipment increases.
4. As the holding cost h_s increases from 6 to18, there are the following major effects: (1) the retailer's order quantity decreases; (2) the maximum backorder quantity decreases.
5. As the demand rate D increases from 600 to 1300, there are the following major effects: (1) the retailer's order quantity increases; (2) the maximum backorder quantity increases; (3) the number of shipment increases; (4) the supplier's total profit increases; (5) the retailer's total profit increases; (6) the supply chain's total profit increases.
6. As the purchasing cost P_R increases from 21 to 63, there are the following major effects: (1) the supplier's total profit increases; (2) the retailer's total profit decreases.
7. As the selling price S_R increases from 48 to 90, there are the following major effects: (1) the retailer's total profit increases; (2) the supply chain's total profit increases.
8. As the specified process capability index of process characteristic K_m increases from 0.5 to 1.2, there are the following major effects: (1) the coefficients of specification limits of process characteristic increases; (2) the supplier's total profit decreases; (3) the supply chain's total profit decreases.
9. As the target value of process characteristic T increases from 398 to 404, there are the following major effects: (1) the coefficients of specification limits of process characteristic increases; (2) the supplier's total profit decreases; (3) the supply chain's total profit decreases.
10. As the maximum mean of process characteristic μ_{max} increases from 401 to 404, there are the following major effects: (1) the supplier's total profit decreases; (2) the supply chain's total profit decreases.
11. As the minimum standard deviation of process characteristic σ_{min} increases from 0.1 to 0.4, there are the following major effects: (1) the quality investment decreases; (2) the coefficients of specification limits of process characteristic vary; (3) the supplier's total profit decreases; (4) the supply chain's total profit decreases.
12. As the maximum standard deviation of process characteristic σ_{max} increases from 0.4 to 0.8, there are the following major effects: (1) the coefficients of specification limits of process characteristic vary; (2) the supplier's total profit decreases; (3) the supply chain's total profit decreases.
13. As the quality investment constant for the standard deviation of process characteristic α increases from 0.02 to 0.04, there are the following major effects: (1) the supplier's total profit increases; (2) the supply chain's total profit increases.
14. As the quality investment constant for the mean of process characteristic β increases from 0.02 to 0.09, there are the following major effects: (1) the coefficients of specification limits of process characteristic decreases; (2) the supplier's total profit increases; (3) the supply chain's total profit increases.

5. CONCLUSIONS AND DISCUSSION

In the present paper, a modified Chuang and Wu's model (2019) is proposed under the specified process capability index C_{pm} value for determining supplier's optimum quality investment and specification limits and retailer's optimum order quantity, number of shipments and maximum backorder quantity with maximization of total profit of supply chain system. This modified model assumes that both improved mean and standard deviation of process characteristic is the declining exponential reduction function of quality investment, and also involves the specified C_{pm} value for assuring the constrained society's loss for shipped products. Based on the sensitivity analysis, it may be seen that the supply chain's total profit is positively influenced by the production rate, the demand rate, the purchasing cost, the selling price and the quality investment, and is negatively affected by the production cost, the specified process capability index, the target value, the maximum mean and both the minimum and the maximum standard deviations of process characteristic.

The management implication of the present work is that a high quality product provided by the supplier can always satisfy customer's requirement, promote the customer's expectation and increase the expected total profit of the supply chain system. The modified model should have higher total profit of supply chain system than that of supply chain model without specified process capability index C_{pm} value. This is because the supplier needs to spend investment cost for assuring the good output quality and satisfying the requirement of customers. The limitation of our modified model is that the quality investment is assumed to be the exponential reduction function of the mean and standard deviation of process characteristic, which is not really reasonable for some situations when there is no quality investment and consequently the long-term quality improvement policy may be violated. For those situations, the short-term product screening should be applied in the modified model. Further extension of the present work may address the case of multi-attribute characteristics in the modified model.

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