

(Q, r) Inventory Model with Embedded Quality Inspection



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Abstract

The classical (Q, r) Inventory model is revisited and the effect of quality changes on lot sizing are discussed. The lots received from the supplier suffer from a known proportion of defectives and each lot is accepted after passing through a single sampling plan of the attribute type with rectification. The lot size Q is a part of this exercise and the parameters (n, c) of the plan are determined. An iterative procedure is developed to simultaneously determine n, c, Q and r of the model. The working of the model and the sensitivity are numerically illustrated.

Keywords: (Q, r) Inventory model, Fraction defective, Consumer's risk, Rectifying inspection, Average Total Inspection.

1. Introduction

In the recent years there is a growing interest in the study of inventory models with embedded quality aspects. In a typical supply chain it is often required to meet the demand as and when it arises and any deviation from quality leads to lack of supply. This needs quality inspection of received lots before they are put to use.

Very often, in case of several consumer goods, a high level of inventory does not mean a high sales/usage rate. Customers may reject some of the items on the shelf when they do not confirm to the quality expectations. As a result, the stockiest has to make sure that quality of the lot is acceptable before putting it for sale/consumption.

Some basic references in this direction are Silver (1974), Wie Shih (1980), Kalro and Gohil (1982) etc.

Sometimes the quantity received will be uncertain due to quality problems while in some cases the supplier makes an excess-supply than what is asked, in order to make up for the possible defectives. If the quality is not up to the mark in the lot, the stockiest may accept the lot but not at the quoted price and claims a price-discount as a sort of compensation for poor quality. Though this not always the case, the usage/consumption rate would be altered by consuming extra quantity to get the same output. This happens, when the management decides not invite shortages by rejecting a lot. A similar situation occurs in sales context, when the stockiest offers extra quantity for the same price possibly to cover up a low quality. When the customer compares the price and quality, these types of incentives often work well. The interesting aspect of this type of sales is that the demand distribution drifts to the right or left of its central value. Mohan Naidu and Sarma (1997) have worked on an inventory problem with this type of drifted demand. Jaggi and Mittal (2011) have addressed the problem of determining the economic order quantity for deteriorating items assuming that the items suffer from imperfect quality. Recently Sunitha and Sarma (2012) have studied the problem of determining the EOQ when the lots are subject to rectifying inspection with attribute type single sampling plan. They have included the sampling plan parameters as part of the EOQ model. A fixed order quantity system with lot size Q can have a positive reorder point (r) when there is a significant but random lead time. This is called (Q, r) model and can be operated by a continuous review. The demand during the lead time can be described by a random variable X having a stationary demand distribution with density function $f(x)$. When the stock level is monitored continuously we never miss the ROP and hence this approach is called the *continuous review policy*. Johnson and Montgomery (1974) gave a detailed working of this model assuming that the lead time distribution has normal distribution.

In this paper, we study a (Q, r) inventory model governed by a deterministic demand but having an uncertain lead time such that shortages during the lead time are backlogged. We determine the optimal values of the lot size Q and the reorder point r by exploiting the computational features of using Poisson OC-curve of the sampling plan. A computer program (given in appendix) is also developed to run experiments with different input parameters, to understand the working of the model.

2. Notation, Assumptions and Problem Environment

The following notation is used to understand the basic (Q, r) model and the developments made in this paper.



Inventory aspects:

- A = Fixed ordering cost per order
- D = Expected demand during the cycle
- h = unit holding cost per unit per unit time
- π = unit cost of due to a sing item that is backlogged
- L = Fixed lead time (in suitable units)
- Q = Fixed order quantity
- r = Re order point
- X = Random variable describing the demand during lead time
- μ = Mean demand during lead time
- $E(t)$ = Expected length of inventory cycle

Quality aspects

- p = known fraction defective in the lots
- RQL = Rejectable Quality Level
- β = Consumer's risk
- n = sample size to be drawn from the lot of Q
- λ = Mean of the Poisson distribution in the type-B OC function
- c = critical number for lot sentencing
- P_a = Probability that a lot is accepted basing on the sampling plan
- ATI = Average Total Inspection
- g = Unit cost of inspection
- ν = penalty when a defective item reaches the customer

The following assumptions are made

1. The lot relieved may contain items that can be classified as defective or non defective basing on a test
2. The fraction defective of the lots is known, from the vendors supply history.
3. Whenever a lot is received, it is subject to a single sampling plan with using Rectifying inspection.

4. Defectives are segregated out and returned to the supplier (at the cost of the supplier) before taking into stock.
5. Shortages occur during the lead time only
6. All shortages are backlogged

The system operates as follows.

The received lot is subjected to acceptance sampling using a *Single Sampling Plan*. A sample of n units are inspected at random from the lot and the lot is accepted if number of defectives in the sample is less than or equal to c . The lots from the supplier contain a known fraction defective p . The inspection is assumed to be error-free and the probability of accepting a lot is P_a . The inventory situation is shown in figure-1. When the lot is accepted, the defectives found in the sample can't be replaced immediately and they are kept aside for replacement by the supplier or they are taken back by the supplier at no extra cost at the time of next delivery. As a result the un-inspected portion of every accepted lot contains $p(Q-n)$ units on an average. These defectives may reach the customer during sales. If a defective reaches the customer, there is a penalty cost of ν per unit.

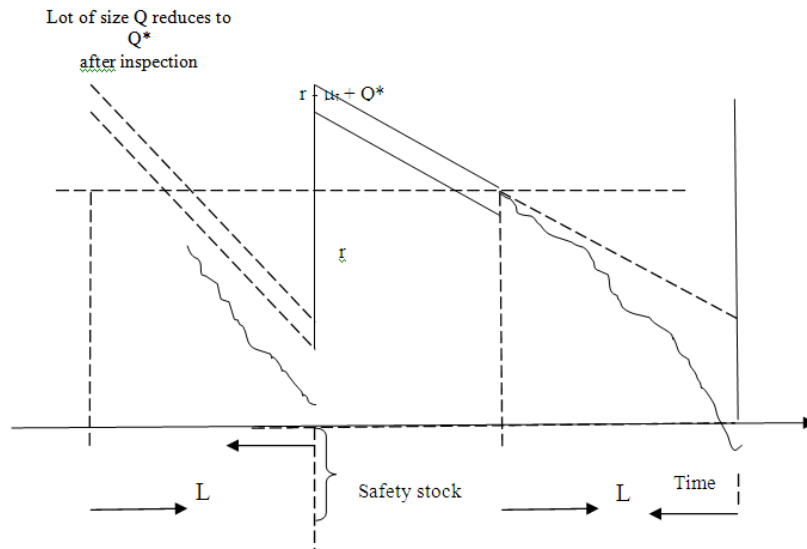


Figure-1: Inventory situation for the (Q,r) model under quality inspection

The expected cost of defectives that would reach the customer becomes $\nu p P_a (Q-n)$ and this increases linearly with Q . When the lot is rejected after sampling inspection, 100 % inspection is carried out by inspecting the remaining $(Q-n)$ units. This is the conventional concept of rectifying inspection, which is better applicable for a

production system in which there is a provision for replacement of defective items with good items. However in the case of purchased items from a supplier, the defectives cannot be replaced, because good items for replacement are not immediately available. Sekhar, Sarma and Goyal (1995) have studied a situation of this type, where rectification leads to a reduced lot size in a two-stage production system. In a recent paper Sunitha and Sarma (2012) have established the following proposition.

Proposition-1: The expected lot size available for sales/consumption is given by $Q' = (1-p)P_a(Q-n) + Q(1-p)(1-P_a)$ and $Q' \leq Q$. The equality holds when all the defectives are replaced by good items.

The expression given in proposition -1 determines the expected cycle length as $E(t) = \frac{Q'}{D}$ which leads to complicated expression for optimization. We therefore adopt an approximate form to $E(t)$ with the following argument.

The costs that arise due to inspection will be as follows.

- a) Since every accepted lot contains $(Q-n)$ items uninspected, the fraction defective that reaches the customers from the accepted lot is simply the Average Outgoing Quality (AOQ) given by $p' = p P_a(Q-n)$.
- b) The expected number of defectives that reaches the customer will be $p' Q$ and the cost due to these defectives is $v p P_a(Q-n)$.
- c) The average number of items inspected either in sampling or in screening is called the Average Total Inspection is given by $ATI = n + (Q-n)(1-P_a)$. Since the inspection cost is g per unit, the cost of inspection in any cycle will be $g[n + (Q-n)(1-P_a)]$.
- d) The ATI is convex in shape with respect to c and hence the optimal critical value c^* is located at the minimum of ATI.
- e) For evaluating P_a , we can use type-B OC curve using Poisson distribution assuming that Q is large when compared to n . This needs estimation of Poisson mean λ .

Given the lot size Q and other parameters p , RQL and β we find the optimal n and c with the following algorithm.

Algorithm-1:

1. Start with $c_0 = 0$

2. Find λ at this c by using either tables of cumulative Poisson distribution or Excel function, using β as the required probability.
3. Calculate $n_0 = \lambda/RQL$ so that the trial plan will be (n_0, c_0) where $c_0 = 0$
4. Find P_a , the probability of acceptance with this n and c using Poisson tables or Excel function, POISSON (x, mean, cumulative)
5. Calculate $ATI = n_0 + (1 - P_a)(Q_0 - n_0)$
6. Put $c = c_0 + 1$ and repeat the above steps until ATI reaches a minimum.

The Excel worksheet has a built in function to calculate λ using the relationship $2\lambda = \text{Inverse of } \{\text{CHI}(2(c+1), 1-\omega)\}$ (see Mittag and Rinne (2001)) where $2(c+1)$ is the degrees of freedom and $(1-\omega)$ denotes the critical probability.

The above algorithm will be incorporated in the cost function that operates with the (Q, r) system which is outlined in the following section.

3. Review of the (Q, r) Inventory Model

Consider an inventory situation controlled by a continuous review EOQ policy with demand following a known stationary distribution having a stable mean of D units/unit per time. The inventory level is monitored after every transaction and the policy is to order for Q units whenever the inventory level drops to r .

If the items in stock are demanded one at a time or in small quantities, there will be no significant overshoot of the re-order point when it is reached.

All shortages are assumed to be backordered at a cost of π per unit. The average number of cycles per unit time is a random variable that averages D/Q .

By the time the replenishment order is received the amount of the shortage will max $(0, x - r)$. Therefore the shortage cost per cycle becomes $\pi \bar{b}(r)$ where

$$\bar{b}(r) = \int_r^{\infty} (x - r)f(x) dx \quad (1)$$

denotes the expected number of shortages per cycle which is a function of the reorder point r .

The net Inventory is at its minimum $(r - \mu)$ immediately before receipt of an order and maximum $(Q + r - \mu)$ immediately after of an order, where μ is the expected demand during a lead time and the expected inventory held during a cycle will be $\left[\frac{Q}{2} + r - \mu\right]$.

The Inventory carrying cost per cycle is $\frac{hQ}{D} \left[\frac{Q}{2} + r - \mu\right]$ where $\frac{Q}{D}$ is the average length of a cycle.

Since the procurement cost per cycle is A , the expected cost during a cycle becomes

$k(Q) = A + CQ + \frac{hQ}{D} \left[\frac{Q}{2} + r - \mu \right] + \pi \bar{b}(r)$ The optimal values of Q and r are obtained (Johnson and Montgomery (1974) as follows.

$$Q = \sqrt{\frac{2D(A + \pi \bar{b}(r))}{h}} \quad (2)$$

$$\text{And } r \text{ is the solution of } \int_r^\infty f(x) dx = \frac{hQ}{\pi D} \quad (3)$$

Starting with a trail value of $Q = \sqrt{\frac{2AD}{h}}$, (2) and (3) can be solved iteratively.

In the following section we incorporate the effect of quality inspection on the above model.

4. The New Model with Quality Inspection

The optimal Q and r are implicitly related to plan parameters n and c . When a lot is accepted the uninspected portion of the lot contains some defectives when reach the customer and cause penalty. The cost components for accepted and rejected lots will be different with different weights.

Case-1: Accepted lot

When the lot is accepted by the sampling plan, the uninspected portion of $(Q-n)$ units contains only $(1-p)(Q-n)$ items worth consumption and hence the holding cost is based on an average stock of $\frac{(1-p)(Q-n)}{2}$. The inspection cost is gn since only n items are inspected and the penalty for having defective units during consumption will be $vp(Q-n)$. The effective cycle length will be $\frac{(1-p)(Q-n)}{D}$.

The inventory cost in this case becomes

$$K_1(t, Q) = \left[A + \frac{h(1-p)(Q-n)}{D} \left(\frac{(1-p)(Q-n)}{2} + r - \mu \right) + gn \right] + vp(Q-n) + \pi \bar{b}(r) \quad (4)$$

This cost holds good with a probability P_a .

Case-2: Rejected lot

When the lot is rejected all the defectives are separated and the inventory of good items at the beginning of the cycle is approximately $Q' = (1-p)Q$. The effective cycle length in this case will be $\frac{Q(1-p)}{D}$.

The cost component in this case will be

$$K_2(t, Q) = \left[A + \frac{hQ(1-p)}{D} \left(\frac{Q(1-p)}{2} + r - \mu \right) + gQ \right] + \pi \bar{b}(r) \quad (5)$$

This cost holds good with a probability $(1-P_a)$.

Thus the expected inventory in a cycle becomes

$$K(t, Q) = P_a K_1(t, Q) + (1 - P_a) K_2(t, Q) + \pi \bar{b}(r) \quad (6)$$

Assuming that the sample size n is relatively smaller than Q , we can treat $(Q-n) \cong Q$ and hence from proportion-1. $E(t) = \frac{Q'}{D} \cong \frac{Q}{D}$

Multiplying by D/Q the number of cycles during the period, the cost per unit time becomes

$$\begin{aligned} K(t, Q) = & \frac{AD}{Q} + CD + \frac{hQ(1-p)^2(1-P_a)}{2} + hr(1-p)(1-P_a) - h\mu(1-p)(1-P_a) + gD - gDP_a \\ & + \frac{hP_a(1-p)^2(Q-n)^2}{2Q} + \frac{hrP_a(1-p)(Q-n)}{Q} + gnP_a \frac{D}{Q} + \pi \bar{b}(r) \frac{D}{Q} + vpP_aD - \frac{nvpP_aD}{Q} \end{aligned} \quad (7)$$

Minimizing $K(t, Q)$ with respect to Q and r leads to the following expressions.

Where

$$Q = \sqrt{\frac{2\{A + \pi \bar{b}(r) + P_a(ng + nvp)\} + nhP_a(1-p)\{n(1-p) + 2(r + \mu)\}}{h(1-p)^2}} \quad (8)$$

where

$$\hat{A} = \{A + \pi \bar{b}(r) + P_a(ng + nvp) \text{ and } M = nhP_a(1-p)\{n(1-p) + 2(r + \mu)\}\}$$

r is the solution of the equation

$$F'(r) = \left\{ \frac{Q}{\pi D} \right\} \left\{ \frac{h(1-p)[Q(1-P_a) + P_a(Q-n)]}{\pi Q} \right\} \quad (9)$$

(8) and (9) can be solved iteratively starting with a trial value of $Q = \sqrt{\frac{2AD}{h}}$. This however requires the knowledge of the distribution of lead time $f(x)$.

Particular cases:

1. Suppose $p = 0$ and $P_a = 1$. Then (8) reduces to $Q = \sqrt{\frac{2\{A + \pi \bar{b}(r)\}}{h}}$ which is the EOQ in the classical (Q, r) system without quality consideration.

2. The equation (9) for the reorder point also reduces to the integral equation of the

$$\text{classical models given by } F'(r) = \frac{hQ}{\pi D}$$

In the following section, we discuss the case of exponential distribution since $F'(r)$ in this case has a closed form expression.

5. The Case of Exponential Distribution for the Lead Time Demand

We consider the case of exponential distribution for the demand during the lead time with mean so that the density is given by $f(x, \lambda) = \lambda^{-1} \exp(-x/\lambda)$, $x \geq 0$, $\lambda > 0$ and 0 otherwise. In this case we get $F'(r) = \exp(-r/\lambda)$.

From (8) it follows that

$$Q = \sqrt{\frac{2D\{A + \pi(\lambda e^{\frac{-r}{\lambda}}) + P_a(ng + nvp)\} + nhP_a(1-p)\{n(1-p) + 2(r + \lambda)\}}{h(1-p)^2}} \quad (10)$$

From (9) it follows that $e^{\frac{-r}{\lambda}} = \frac{hQ}{\pi D}$ so that

$$r = \lambda \log_e \left(\frac{\pi D}{hQ} \right) \quad (11)$$

Given the values of A , D , n , g , v , p we can find the optimal pair (Q^*, r^*) iteratively starting with $\bar{b}(r) = 0$ and trial value of Q as Q_1 where

$$Q_0 = \sqrt{\frac{2D\{A + P_a(ng + nvp)\} + nhP_a(1-p)\{n(1-p) + 2(r + \mu)\}}{h(1-p)^2}} \quad (12)$$

and this gives

$$r_0 = \lambda \log_e \frac{\pi D}{h} \sqrt{\frac{h(1-p)^2}{2D\{A + P_a(ng + nvp)\} + nhP_a(1-p)\{n(1-p) + 2(r + \mu)\}}} \quad (13)$$

The following algorithm is used for optimization.

Algorithm-2:



1. Start with $i=0$
2. Obtain Q_0 and r_0 from (11) and (12)
3. Set $Q_i = Q_0$ and $r_i = r_0$
4. Determine the optimal n and c and P_a using algorithm-1
5. Use (10) and (11) to find new values of Q and r .
6. Repeat until $Q_i = Q_{i+1}$ or $r_i = r_{i+1}$ for some $i \geq 1$
7. The optimal pair is $Q^* = Q_i$ and $r^* = r_i$

In the following section the performance of the model is studied by using a sample data set. Since several Excel functions are required for evaluating the model, a computer code in Visual Basic is developed as given in Appendix-1.

6. Evaluation of the Model Sensitivity

In order to understand the functioning of the model we have used the following data set with all parameters in consistent units.

$$\{A = 50, \pi = 1.5, D = 10000, h = 3, g = 1, v = 5, \text{beta} = 0.1, \mu = 50, \text{RQL} = 0.08\}$$

The behavior of the model is studied by changing the values of selected parameters one at a time keeping other parameters fixed. At each combination of parameters, the values of n , c , Q , r and the minimum cost are calculated.

When the value of the incoming lot changed, the model is expected to produce a higher value of EOQ. This is found true and illustrated in Table-1 and the performance is shown in Figure-1.

It follows from the above illustration that when the quality of the ordered lot becomes poor, both Q and r are found to increase initially, reaches a maximum at an intermediate value of p and then decrease. This is because when p is very small most lots are accepted and when p is very large many lots are rejected but rectified by 100% screening. The optimal cost is however found to increase with lot fraction defective.

p	C	n	Q	r	COST
0.01	2	67	596	89	1401.95
0.02	4	100	611	90	2719.50
0.03	6	132	626	91	4107.28
0.04	8	162	638	92	5547.26
0.05	8	162	634	92	5627.74
0.06	8	162	631	92	5696.53

Table-1: Sensitivity of the model with respect to changes in p

It can be seen from table-1 that when the lot fraction defective increases, more inspection is required. The EOQ as well as the reorder point increase upto $p = 0.04$ and then show a decreasing trend. This is due to the fact, that poorer the lot quality, more lots will be rejected (by the sampling plan) leading to 100% inspection and hence a lower EOQ becomes optimal.

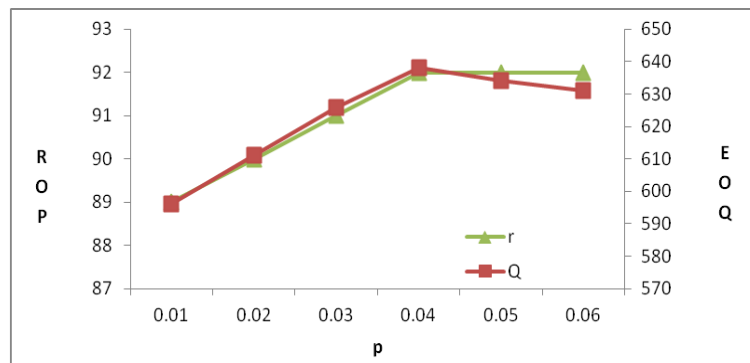


Figure-1: Behavior of Q and r due to changes in p

7. Conclusions

It is established that when the incoming lot quality is poor the stockiest has to order for a higher quantity than what is ordered without quality consideration. The scenario of rectifying inspection arises in reality in many cases of retail business where the stockiest prefers 100% inspection when the lot is rejected by a sample inspection all non conforming items are simply rejected and returned to the supplier. When the lots contain higher fraction defective the inspection cost increases and hence the total inventory cost also increase. The analytical portion of the model developed in this paper is the derivation of sampling plan as part of optimization of the inventory model.

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APPENDIX-1

Visual Basic code for running the (Q, r) mode with embedded single sampling plan

```
Dim A, D, h As Double
Dim q, q1 As Double
Dim lam, mu, r, r1, ltdemand, pi, mean, pa As Single
Dim term1, term2, term3, cost As Single
Dim g, v, p, beta, rql, ATI As Single
Dim n, c As Integer
Dim oxl As Excel.Application
Dim oWord As Object
Dim oDoc As Object
Private Sub Command1_Click()
End
End Sub
Private Sub Command3_Click()
Cls
A = 50
pi = 3.5
mu = 50
D = 10000
h = 3
g = 1
v = 5
p = 0.02
beta = 0.1
rql = 0.08
Call ssp
Me.Command1.SetFocus
End Sub
Private Sub ssp()
Print "A = "; A
Print "D = "; D
```

```

Print "h = "; h
Print "pi = "; pi
Print "mu = "; mu
Print "g = "; g
Print "v = "; v
Print "p = "; p
Print "beta = "; beta
Print "RQL = "; rql
Print
q = Sqr(2 * A * D / h)
cost = Sqr(2 * A * D * h)
Print "basic cost =", cost
Set oxl = CreateObject("excel.application")
c = 0
Do While c <= 10
lam = 0.5 * oxl.Application.ChiInv(beta, 2 * (c + 1))
n = Round(lam / rql, 0)
mean = n * p
pa = oxl.Application.Poisson(c, mean, 1)
ATI = n + (1 - pa) * (q - n)
Call qrmodel
Print c, Format(lam, "#.#####"), n, Format(pa, "#.#####"), ATI, Int(q),
Int(r1), '
'optimal cost
'pa = 1
'p = 0
'n = 0
'g = 0
term1 = (A + c * q + (h * q * (1 - p) / D) * (q * (1 - p) + (r1 - mu)) + g * q) * (1
- pa)
term2 = (A + c * q + (h * (q - n) * (1 - p) / D) * ((q - n) * (1 - p) * 0.5 + (r1 -
mu)) + g * n) * pa
term3 = pi * lam * Exp(-r1 / lam) + v * p * pa * (q - n)

```

```

cost = term1 + term2 + term3
Print cost
c = c + 1
Loop
Me.Command1.SetFocus
End Sub
Private Sub qrmodel()
Dim delta As Single
Dim i As Integer
delta = 0
i = 1
Print
Do While i <= 20
r1 = mu * Log((h * mu * q) / (pi * D))
'new q
n1 = 2 * D * (A + pi * (lam * Exp(-r1 / lam))) + pa * (n * g + n * v * p)
n2 = n * h * pa * (1 - p) * (n * (1 - p) + 2 * (r1 + ltdemand))
Den = h * (1 - p) * (1 - p)
q1 = Sqr((n1 + n2) / Den)
delta = q1 - q
q = q1
i = i + 1
Loop
End Sub

```

Sample output

QR MODEL							
A = 50							
D = 10000							
h = 3							
pi = 3.5							
mu = 50							
g = 1							
v = 5							
p = 0.02							
beta = 0.1							
RQL = 0.08							
basic cost = 1732.051							
0	2.3026	29	.5599	270.3298	590	46	426.853
1	3.8897	49	.7431	188.1905	593	46	930.2368
2	5.3223	67	.8478	147.1445	596	46	1485.974
3	6.6808	84	.9098	130.2802	600	47	2074.252
4	7.9936	100	.9473	126.3721	605	47	2685.49
5	9.2747	116	.9689	131.1973	610	48	3318.017
6	10.5321	132	.9815	140.838	616	48	3970.552
7	11.7709	147	.9893	152.0006	622	49	4640.502
8	12.9947	162	.9938	164.8423	629	49	5331.501
9	14.206	178	.9963	179.6835	637	50	6048.978
10	15.4066	193	.9978	193.9667	646	50	6786.84

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