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The Total Cost Function Of Non-Regular Fixed Lifetime Inventory System

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ABTRACT
This study focuses on developing and analyzing the total cost function for a non-regular fixed lifetime inventory system. Unlike traditional perishable inventory where obsolete items are discarded, non-regular fixed lifetime items (such as hotel rooms, airline seats, and advertising space) are not used to meet demand in one period become outdated but are retained and remain useful in subsequent periods. The core problem addressed is the lack of a comprehensive cost model for such systems and the analytical difficulty in proving the convexity of the resulting cost function, which is crucial for identifying a unique, global minimum cost. The research had four specific objectives: to develop a mathematical model for the total cost function; to determine the convexity of the function using Wolfram Mathematica software; to identify the global minimum point for cost minimization; and to demonstrate the application of the model through numerical enumeration. The methodology involved synthesizing key cost components—ordering cost, holding cost, shortage cost, outdate cost, maintenance cost, discount cost, and fixed operating cost—into a unified total cost function. A critical aspect of the study was the development and application of a computer-assisted algorithm to verify the function's convexity by analyzing the Hessian matrix of its second-order partial derivatives. The key findings are: (1) A robust total cost function model for non-regular fixed lifetime inventory was successfully derived. (2) The Hessian determinant was proven to be non-negative (/(\det(H) \ 0)\) for positive values of the variables, confirming the function's convexity and ensuring the existence of a unique global minimum. (3) Numerical examples using Wolfram Mathematica demonstrated the model's practical application, calculating total costs for scenarios in the transportation sector (e.g., a train with 1000 seats and a bus with 40 seats). The study concludes that the total cost function for non-regular fixed lifetime inventory is convex, which allows businesses to determine the optimal operating point that minimizes cost. This model provides a valuable decision-support tool for managers in service industries to analyze, control, and optimize their cost structures, ultimately leading to reduced wastage, prevention of shortages, and enhanced profitability. The research bridges a significant gap in inventory theory by moving beyond revenue-focused models to provide a cost-based optimization framework for reusable, time-sensitive inventory assets.
Keywords: total cost function, inventory system, non-regular fixed lifetime

INTRODUCTION

Background: Inventory systems are crucial for balancing stock to meet demand without overstocking. Non regular Fixed lifetime Inventory Definition: Items that become outdated after a period but are not discarded and remain available for the next period. Examples: Hotel rooms, airline seats, advertising space. Core Issue: Existing research focuses on revenue, not the underlying cost structure.

Statement of Problem

Many businesses fail due to an inability to analyze operating costs comprehensively.

Existing inventory models often lead to discarded obsolete items, causing shortages.

Previous authors (Hariga, 2010; Mahmoodi et al., 2015) claimed their cost functions were not convex.

This research: Proposes a total cost function for Non Regular Fixed Lifetime Inventory and verifies its convexity via a computer-based approach.

Research Objectives

General Objective:

To develop a mathematical model for the total cost and verify its convexity for Non Regular Fixed Lifetime Inventory.

Specific Objectives:

- Develop the total cost function mathematical model.
- Determine convexity using Wolfram Mathematica.
- Find the global minimum point for cost minimization.
- Estimate the total cost using the developed model.

Significance Of The Study

Determining the efficiency of production processes, with the study of total cost function, it will help industries to know the cost incurred during the production of a product or rendering of a particular service. Further the modalities to minimize the total cost will be their major priority while still maintaining the same standard of business.

This research is set to addresses the issue of discarding unused items, which can lead to shortage in business, instead items can be used in another time that is when the non-regular fixed lifetime inventory come to place. Items are only depleted by demand, not discarded.

RESEARCH METHODOLOGY

Introduction

This section involves developing a mathematical model for the total cost function of a non-regular fixed lifetime inventory system. This is achievable by addition of all the cost components. Also we also propose an algorithm for convex function using the Hessian Matrix which will be use to test the convexity of our total cost function in chapter four of this research.

Model Description

The total cost function model for non regular fixed lifetime inventory is generated by the addition of all the cost components. The cost component are; ordering cost, shortage cost , holding cost, maintenance cost, fixed operating cost, discounting cost, outdate cost.

Ordering Costs:

It can be expressed mathematically as;

$$\boldsymbol{c \times y} \qquad (3.1)$$

where; $\boldsymbol{c}$= ordering cost , $\boldsymbol{y}$ = new booked items on the day of render of service

3.1.2 Holding Costs (Carrying Costs): It can be expressed mathematically as;

$$\boldsymbol{h\int_0^{x+y}(x+y-t)f(t)dt} \qquad \textbf{(3.2)}$$

where;

x= previously booked items, y= available booked items on the day of render of service

h=holding cost, $f(t)$= probability density function (PDF).

Stockout Costs (shortage cost): These are the costs incurred when inventory runs out, it can be represented mathematically as;

$$r\int_{x+y}^{\infty}(t-(x+y)f(t)dt \qquad (3.3)$$

where; r= shortage cost , x= previously booked y= available booking items on the day of render of service. $f(t)$= probability density function (PDF).

Outdate Cost; for every product not used to satisfy demand at the end of its useful-lifetime in inventory, an outdate cost is charged against the inventory manager.

$$\theta\int_{0}^{y} f(t+x)F(y-t)\,dt \qquad (3.4)$$

where; θ= outdate cost, x = previously booked items, y = available booking on the day of render of service, $F(t)$= cumulative distribution function.

Maintenance Cost

Reusable inventory items (e.g., hotel rooms, airplane seats) require periodic maintenance to remain functional. This includes cleaning, repairs, and upgrades.

Formulation;

$$\mathbf{M_c = m.(x+y)} \qquad \textbf{(3.5)}$$

where; $\mathbf{m = maintenance\ cost\ per\ unit}$, $\boldsymbol{x} = \mathbf{previously\ booked\ items}$

$\boldsymbol{y = available\ booking\ on\ the\ day\ of\ render\ of\ service}$

Discounting Cost

To avoid outdate, the company may offer last minute discount (e.g unsold train seat at lower prices). This reduced revenue but minimized losses.

Formulation; $D_c = d.\int_0^y F(x-t)dt$ (3.6)

where; $d = discount\ cost\ per\ unit$

Fixed Operating Cost

This include fixed overhead cost like administrative expenses, utility and staffing, independent of inventory levels.

Formulation; $F_c = K$ **(3.7)**

Total Cost Function

The total cost function (T_c) for non-regular fixed lifetime inventory system is the sum of all these costs:

$$T_c = O_c + H_c + U_c + S_C + M_c + D_c + F_c \quad (3.8)$$

where: T_c = Total cost, O_c = Ordering costs, H_c= Holding costs, U_c= Outdate costs, S_C= Stockout costs, M_c =maintenance cost, D_c = discount cost, F_c =fixed operating cost, Therefore it can be represented mathematically as;

$$T(x,y) = cy + h\int_0^{x+y}(x+y-t)f(t)dt + r\int_{x+y}^{\infty}(t-(x+y)f(t)dt + \emptyset\int_0^{y} f(t+x)F(y-t)dt + d.\int_0^{y} F(y-t)dt + m.(x+y) + K$$

(3.9)

Probability Density Function (PDF)

$f(t)$ =probability density function (PDF) for uniform distribution

For a uniform distribution over (a,b) the PDF of $f(t)$ is constant

$$f(t) = \frac{1}{b-a} \qquad (3.10)$$

$a = minimum\ point$

$b = maximum\ point$

3.2.2 Cumulative Distribution Function (CDF)

$F(t)$ =cumulative distribution function (CDF) for uniform distribution

The CDF $F(t)$ gives the probability that demand $T \geq t$

$$F(t) = P(T \leq t) = \int_a^t f(u)du \qquad (3.11)$$

Substituting the value of $f(u) = f(t)$

The CDF $F(t)$ is used in;

Outdate cost because $F(y-t)$ represent the probability that the remaining inventory $(y-t)$ is not fully demanded.

3.3. Convex Function

Definition; let X be a convex set in a real vector space and let f:X→R be a function. F is called convex if;

$$x_1\ , x_2\ \epsilon\ X, t\epsilon\ \ 0,1\ \ :\ f(\ tx_1\ +\ (1-t)\ x\ \leq\ tf(x_1)\ +\ (1-t)f(x_2)$$

This necessary and sufficient condition and the basic definition of convex function are useful for examining if a function of a single variable is convex. The necessary and sufficient condition is when the function is twice differentiable and the second derivative is greater than or equal 0. The second derivative must not be negative value.

Definition ; Let *f* be the twice differentiable function of n variables.

$$\text{Hessian of } f \text{ at } x \text{ is } \boldsymbol{H_m}(x) = \begin{Bmatrix} F_{11}(x) & f_{12}(x)\ldots\ldots f_{1n}(x) \\ F_{21}(x) & f_{22}(x)\ldots\ldots f_{2n}(x) \\ F_{31}(x) & f_{32}(x)\ldots\ldots f_{3n}(x) \\ \ldots\ldots & \ldots\ldots \quad \ldots\ldots \\ F_{n1}(x) & f_{n2}(x) \quad f_{nn}(x) \end{Bmatrix}$$

3.3.1. Algorithm for Convex Functions

We proposed a method for showing that the total cost function is convex. The steps are as follows;

STEP1; input the total cost function for the model.

STEP 2; obtain the first order partial derivatives of the total cost function

STEP 3; from step 2, obtain the second order partial derivatives of the total cost function

STEP 4; Form the Hessian matrix of the total cost function from the second order partial derivatives obtained in step 3.

STEP 5; obtain the determinant of the Hessian matrix ($\boldsymbol{H_m(x)}$).

STEP 6; if the determinant of the $\boldsymbol{H_m(x) \geq 0}$, then the total cost function is convex, otherwise, the total cost function is not convex.

Remark; the algorithm above is applicable to functions that are twice differentiable.

To obtain relevant partial derivatives of the total cost function, we used Wolfram MATHEMATICA 8, the software has routines for obtaining partial derivatives and can also evaluate the determinant of a Hessian matrix.

Convexity Analysis

Using the definition and algorithm stated in chapter 3 we can verify if our total cost function is convex. Hence we input the total cost function on the Wolfram Mathematics Software package, run the sequence of operation and plot the graph of the total cost function.

$$T(x,y) = c * y + h * \text{Integrate}[(x+y-t)f(t),\{t,0,x+y\}] + r * \text{Integrate}[(t-(x+y))f(t),\{t,x+y,\text{Infinte}\}] + \theta * \text{Integrate}[F(t+x)F(y-t),\{t,0,y\}] + d * \text{Integrate}[F(y-t),\{t,0,y\}] + m * (x+y) + k$$

Outcome;

$$k + cy + \frac{1}{2}dFy^2 + m(x+y) + h(\frac{fx^3}{6} + \frac{1}{2}fx^2y + \frac{1}{2}fxy^2 + \frac{fy^3}{6}) + r(\frac{f\text{Infinte}^3}{3} - \frac{1}{2}f\text{Infinte}^2x + \frac{fx^3}{6} - \frac{1}{2}f\text{Infinte}^2y + \frac{1}{2}fx^2y + \frac{1}{2}fxy^2 + \frac{fy^3}{6}) + (\frac{1}{2}F^2xy^2 + \frac{F^2y^3}{6})\theta$$
(4.2)

Take the first derivatives with respect to y;

$$c + m + dFy + h(\frac{fx^2}{2} + fxy + \frac{fy^2}{2}) + r(-\frac{f\text{Infinte}^2}{2} + \frac{fx^2}{2} + fxy + \frac{fy^2}{2}) + (F^2xy + \frac{F^2y^2}{2})\theta \quad (4.3)$$

Take the second derivatives with respect to x;

$$h(fx+fy) + r(fx+fy) + F^2y\theta \quad (4.4)$$

Therefore; /H/= $h(fx+fy) + r(fx+fy) + F^2y\theta$ (4.5)

For value of $x > 0, y > 0, r > 0, h > 0, f \geq, F \geq 0$

The determinant is positive for positive value of the variables therefore the function is convex.

Numerical Examples on Convexity Analysis

Example 1

Taking the values of the variables as follows; $x = 8, y = 7, f = 0, F = 0, h = 12, r = 10, \theta = 9$

Solution

Calculating the determinant using the above values;

$h(fx+fy) + r(fx+fy) + F\text{^}2\ y\theta$

H_m=12*(0*8+0*7)+10*(0*8+0*7)+0*0*7*9

H_m=12*0+10*0+0*0

The determinant(H_m) =0

For a function to be convex the determinant most be greater or equal to 0, that is;

$H_m \geq 0$

Numerical Illustrations on Total Cost Functions

To illustrate the application of the model, consider a numerical example from the transportation sector.

Problem 1

A train running on a daily basis with a capacity of 1000 seat per trip incur the following expenses on a daily basis, ordering cost of 5000 naira per seat, with a holding cost of 2000 naira per seat, outdate cost of 3000 naira per seat and also shortage cost of 10000 naira per seat, maintenance cost of 1500 per seat, 4000 discount per seat for last minute booking, fixed operational cost of 50000 naira, 100 seats were booked before that day of departure while 900 seat are available to be booked on the day of departure, demand following a uniform distribution, having a minimum demand of 500 passengers, and a shortage demand of 100 passengers, enumerate the total cost function using the develop total cost function model.

Solution

Considering the total cost function model below;

$$T(x,y) = cy + h\int_{0}^{x+y} (x+y-t)f(t)dt + r\int_{x+y}^{\infty}(t-(x+y)f(t)dt + \emptyset\int_{0}^{y} f(t+x)F(y-t)dt + d.\int_{0}^{y} F(y-t)dt + m.(x+y) + K$$

Steps;

outline of parameters;

ordering cost $c = 5000$ per seat, holding cost $h = 2000$ per seat, shortage cost $r = 10000$ per seat, outdate cost $\theta = 3000\ per\ seat$, maintenance cost $m = 1500\ per\ seat$, discount cost $d = 4000\ per\ seat$, fixed operating cost $K = 50000$, shortage demand=100 seat, seat that has been previously book before the day of departure$(x) = 100$, seat booked on the day of departure $(y) = 900$, Total available seat $(x+y) = 1000$, Minimum demand=500, Maximum demand= $shortage\ demand + x + y$ =1100=∞

calculate the probability density function (pdf) for the distribution;

for a uniform distribution over (a, b) the pdf $f(t)$ is constant;

$$f(t) = \frac{1}{b-a}$$

$$f(t) = \frac{1}{1100-500}$$

$$f(t) = \frac{1}{600}$$

Calculating the CDF $F(t)$, probability demand $T \leq t$

$$F(t) = P(T \leq t) = \int_{a}^{t} f(u)du$$

Substituting $f(u) = \frac{1}{600}$

$$F(t) = \int_{500}^{t} \frac{1}{600} du = \frac{1}{600}(t-500)$$

Thus; $F(t) = \frac{t-500}{600}$

We are going to use figures above to enumerate our total cost function
This analysis will be done using the Wolfram Mathematica Software application to generate result.
Analysis of problem 1

T(100,900)=
$5000 * 900 + 2000 * \text{Integrate}[(100 + 900 - t)\frac{1}{600}, \{t, 0{,}1000\}] + 10000 * \text{Integrate}[t - (100 + 900)\frac{1}{600}, \{t, 1000{,}1100\}] + 3000 * \text{Integrate}[(\frac{1}{600} * \frac{900-t}{600}), \{t, 0{,}900\}] + 4000 * \text{Integrate}[(\frac{900-t}{600}), \{t, 0{,}900\}] + 1500 * (100 + 900) + 50000$

Total Cost of running the train for the period =1058753375

Problem 2

A transport company running from Benin city to Abuja on a daily basics incur the following expenses on some of their buses on a daily basis, ordering cost of 700 naira per seat with a holding cost of 550 naira per seat, outdate cost of 400 naira per seat, and also shortage cost of 300 naira per seat, maintenance cost of 50 naira, and a discounting cost of 800 naira with a fixed operating cost of 10000 naira, previously booked seat is 10 while 30 is available for booking on the day of departure, enumerate the total cost function using the develop total cost function model.

Solution

ordering cost $c = 700$ per seat, holding cost $h = 550$ per seat, shortage cost $r = 300$ per seat, outdate cost $\theta = 400\ per\ seat$, maintenance cost $m = 50\ per\ seat$, discount cost $d = 800\ per\ seat$, fixed operating cost $K = 10000$, x =10(seat that has been previously book before the day of departure), seat booked on the day of departure(y)=30

Total available seat $(x + y) = 40$, Minimum demand=15, Maximum demand= $x + y$ =40

Calculate the probability density function (pdf) for the distribution;

for a uniform distribution over (a, b) the pdf $f(t)$ is constant;

$$f(t) = \frac{1}{b - a}$$

$$f(t) = \frac{1}{40 - 15}$$

$$f(t) = \frac{1}{25}$$

Calculating the CDF $F(t)$, probability demand $T \leq t$

$$F(t) = P(T \leq t) = \int_a^t f(u)du$$

Substituting $f(u) = \frac{1}{25}$

$$F(t) = \int_{15}^{t} \frac{1}{25} du = \frac{1}{25}(t - 15)$$

Thus; $F(t) = \frac{t-15}{25}$

Note; Using the data above to calculate the total cost function, still using the Wolfram Mathematica Software. But in this example we are going to calculate each of the cost separately then add all together to get the total cost function, the reason for this is for us to be able to view each cost as it affect the overall total cost.
Ordering cost

$$c * y$$

$$700 * 30$$

$$ordering\ cost = 21000\ naira$$

Holding cost;

$$h \int_{0}^{x+y} (x + y - t) f(t) dt$$

Since demand is uniform between 15 and 40, we adjust the integral bound to 15-40 (since $x + y = 40$

Using the wolfram mathematica software;

We input the values;

$$550 * \text{Integrate}[(10 + 30 - t)\frac{1}{25}, \{t, 15{,}40\}]$$

$holding\ cost = 6875$ naira

shortage cost

$$r \int_{x+y}^{\infty} (t - (x + y) f(t) dt$$

Input the values on the software package;

$$300 * \text{Integrate}\left[\frac{(t-40)1}{25}, \{t, 40{,}40\}\right]$$

Shortage cost; 0

The shortage cost was zero (0) because available seat was enough to meet demand without looking for extra ways of satisfying customers.

Outdate Cost

$$\theta \int_0^y f(t+x)F(y-t)dt$$

Input the values into the equation above;

$$400 * \text{Integrate}\left[\frac{\left(\frac{30-t}{25}\right)1}{25}, \{t, 0{,}30\}\right]$$

Outdate cost= 288 naira

Discount cost;

$$D_c = d.\int_0^y F(x-t)dt$$

Input the values into the equation above;

$$800 * \text{Integrate}\left[\left(\frac{30-t}{25}\right), \{t, 0{,}30\}\right]$$

Discount cost= 14400 naira

Maintenance Cost;

$$m.(x+y)$$

Input the value into the equation above; $500 * (10 + 30)$

Maintenance Cost= 20000 naira

Total cost = $21000 + 6875 + 0 + 288 + 14400 + 20000 + 10000$

Total cost= 72563

Findings

The findings of this research are as follows:

i) The total cost function for the non regular fixed lifetime inventory system was obtained through the summation of all the total cost components ranging from the ordering cost, holding cost, outdate cost, shortage cost, discount cost, maintenance cost to fixed operating cost.

ii) The developed total cost function mathematical model was tested for convexity following the procedure for test for convexity and we succeeded in showing that it was convex.

iii) Since the total cost function has its second derivatives always positive it means it has a global minimum. This will help in achieving the most cost efficient decision in an organization.

iv)The total cost function developed was use to calculate total cost function of some numerical examples which help business to actualize their aims(minimizing cost and maximizing profit) .

DISCUSSION

- Since the total cost function has it second derivatives always positive it means it has a global minimum. Global minimum is the point where the minimum cost function lies. It is where the total cost is at its lowest possible value across all feasible solution. It represent the best possible decision that minimize cost in an optimization problem. This will help in achieving the most cost efficient decision in an organization. This is also important in other for business to maintain competitiveness in the market.
- The Total cost function was calculated using the total cost function model generated, this will help to drive the company to actually their aims (minimizing cost), this total cost function can be applied by business to test run their total cost in the company, adding other necessary values and parameters if need be, and with time company will be able to know the right values to get minimum cost in running the business and making maximum profit. The data above, total cost function for problem 1 was , all the cost function where calculated simultaneously using the total cost function formulated. Problem 2 highlighted each cost function, that is each of the cost function ranging from ordering cost to fixed operating cost where calculated separating, it was done this way so that business managers and researchers can see each values of individual cost function and know their impact on the overall total cost function and also look for ways to adjust cost if need be.
- From the problem 2 we can see that the ordering cost was; 21000 naira, holding cost was; 6875 naira, shortage cost was; 0 naira, outdate cost was; 288 naira, discount cost was; 14400 naira, maintenance cost was; 20000 naira and fixed operating cost was; 10000 naira therefore the total cost was; 72563 naira. Form the problem2 we can see that the shortage cost zero (0) because available items (seat) was enough to satisfy customer need, so no shortage occurs. Series of calculation like this will help business managers and researchers to know the total cost that will best profit the company.

CONCLUSION

This study has successfully developed a total cost function model which was subjected to convexity test to ascertain if the total cost function model was convex or not. It was found to be convex meaning that minimum cost can be obtain using this model. We can therefore concludes that the total cost function for non-regular fixed lifetime inventory system is convex. This convexity property ensures that any local minimum found is a global minimum, providing a reliable basis for cost minimization. The model offers a practical tool for business in service industries to optimize their inventory management decisions, reduce cost and improve profitability.

Contributions to Knowledge

This research contributed to knowledge in the following ways:

i) It has developed a robust Total Cost Function Mode that innovatively integrates seven critical cost components.
ii) The study has resolved a long-standing analytical challenge through a computer-assisted proof to analyze the Hessian matrix of the second-order partial derivatives.
iii) The study has demonstrated practical application with decision support insight, the research uses numerical illustration to enumerate the total cost, offering a clear decision support tools for industry practitioners.
(iv) By definitively establishing the convexity of the total cost function, this research guarantees that any local minimum identified is also a global minimum thereby providing a reliable framework to identify the unique optimal operating points that minimizes total costs.

RECOMMENDATION

Based on the findings of this study, the following recommendations are made:
i). Business using non-regular fixed lifetime inventory system should adopt the developed total cost function model to analyze and optimize their cost structures.
ii). Managers should pay attention to the cost parameters as they determine the total cost in running the business.
iii). Managers should not just focus on revenues generated from business both also consider total cost spent to generate that revenue that will help them to know if really the company will go bankrupt or not.
iv). Total cost function models should be subjected to convexity test, this will help to know if the cost function will yield a minimum cost or not.

Further Research

i). Future research should explore the application of the model in other industries, such as healthcare and hospitality to validate its generalization.
ii). Further studies could extend the model to include stochastic demand and random lifetime consideration, increasing its application to real world scenarios.
iii). Future research can explore other cost function associated with area of research and also subject the total cost to convexity test to get the required minimum cost.
By addressing all these areas further research can expand and refine total cost function models.

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