Communications on Applied Nonlinear Analysis
ISSN: 1074-133X
Vol 31 No. 6s (2024)

Humanitarian Food Logistics: An Inventory Model for World Food Program (WFP) Operations in Boko Haram-Controlled Areas

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Article History:

Received: *17-06-2024*

Revised: *15-07-2024*

Accepted: *06-08-2024*

Abstract:

This paper examines the critical inventory management situation for the World Food Program (WFP) under the stronghold of Boko Haram terrorists. However, inventory management under such a manmade disaster and the arduous task required additional costs of transportation services for the foodstuff to the various destinations that had to involve military assistance as a backup with a significant increase in holding/carrying costs and the ordering cost. The safety of the humanitarian workers (WFP) and the foodstuff consignment are paramount. Considering this scenario, an attempt has been made to formulate an inventory model for foodstuffs with a constant deterioration rate and seasonal demand rate to optimize the performance of the World Food Program's relief supply chain.

Keywords: Inventory model, WFP, Boko Haram terrorist, foodstuffs, constant deterioration rate, seasonal demand rate.

1. Introduction

In recent decades, insecurity and terrorism have become significant issues in many democratic countries, particularly following the World Trade Center attacks in the United States on September 11, 2001. Socio-political factors have contributed to the rise of organized crime, notably the Boko Haram group. The World Food Program (WFP) is essential in providing relief supplies and food aid, and is the largest NGO focused on humanitarian assistance in crisis regions.

Inventory, which includes goods, products, and raw materials for WFP's relief operations, requires effective management of storage and processing. Efficient inventory control is vital for businesses of all sizes, involving decisions on reorder timing, order quantities, pricing, and sales strategies. In the grain market, where the WFP is active, wholesalers buy grains at lower prices and sell at higher prices when market conditions are favorable.

As a leading humanitarian NGO, the WFP has motivated decision-makers to improve their relief supply chain by optimizing inventory and distribution management. Yang et al. (2024) developed an Economic Order Quantity (EOQ) model for perishable items in cold chain operations. Jaggi et al.

(2010) explored the EOQ model for perishable goods with quality issues and permissible payment delays. Yankah et al. (2022) studied inventory management's impact on the performance of manufacturing firms in Ghana, highlighting its relationship with competitive advantage and organizational success.

Neira et al. (2017) created a mathematical model for product mixing and lot-sizing under uncertain demand. Sanjari-Parizi and Bashirzadeh (2020) developed models for lot-sizing and optimal production. Kumar et al. (2022) reviewed optimal ordering policies for deteriorating inventory with lead times and different payment strategies. Senapati (2017) designed a marketing-focused inventory model considering component demand and time-dependent partial backlogging. Choudhury and Mahata (2024) proposed models for non-instantaneous deteriorating items with fixed lifetimes under hybrid prepayment and trade credit in supply chains.

Competition and flexibility are crucial for gaining a business edge and meeting market demands. As global competition intensifies, buyers increasingly seek customization and shorter product life cycles. Mahata et al. (2018) explored optimal replenishment and credit policies in supply chain inventory models under trade credit with time- and credit-sensitive demand. Jaggi and Singh (2020) devised an inventory relief chain model addressing deterioration and disposal of relief goods.

Recent studies have examined strategies for retailers to adapt to changing times. Jaggi et al. (2015) analyzed the impact of deterioration on two-warehouse inventory models with imperfect quality. Zhong et al. (2017) investigated food supply chain management systems and future research directions. Schiraldi et al. (2009) focused on inventory control policies for humanitarian logistics, emphasizing warehouse safety.

In real-world scenarios, demand fluctuates due to the timing and nature of disasters. Taheri-Tolgari et al. (2012) extended an inventory model for imperfect items under inflation, considering inspection errors in production. S. Gupta et al. (2020) elaborated on EOQ models.

This research highlights the development of decision models for supply chain issues. In this context, we consider an inventory model for foodstuffs with a constant deterioration rate and seasonal demand to optimize the WFP's relief supply chain. Our goal is to show how mathematical analysis can help create optimal policies for managing inventory systems.

Assumptions And Notations

The following assumptions are used in the development of the model.

- The inventory system involves only one item.
- Items are withdrawn continuously at a constant rate of R per unit of time.
- Shortages are not allowed.
- Replenishment of stock level is instantaneous concerning time.

Notations

- C is the Purchasing Cost.
- C_h is the Holding Cost.
- A is the Ordering Cost.

- S(t) is the Inventory Level at any time t.
- t_1 is the Inventory Depletion time.
- φ is the Deterioration Rate.
- D_0 is the Deterioration value per order.
- SS is the Safety stock.
- TC is the Total Inventory Cost.
- S is the Total Ordered Quantity.
- Z is the service level factor (1.65 for 95% service level).
- $\sigma_L$is the Lead time demand variability (10% of monthly demand).

2. Mathematical model and analyses.

The present inventory system S items are procured at the beginning of the relief materials distributions by the World Food Program (WFP). We also consider φ as the rate of defective or deteriorating items, the behavior of the inventory level is shown in Figure 1.

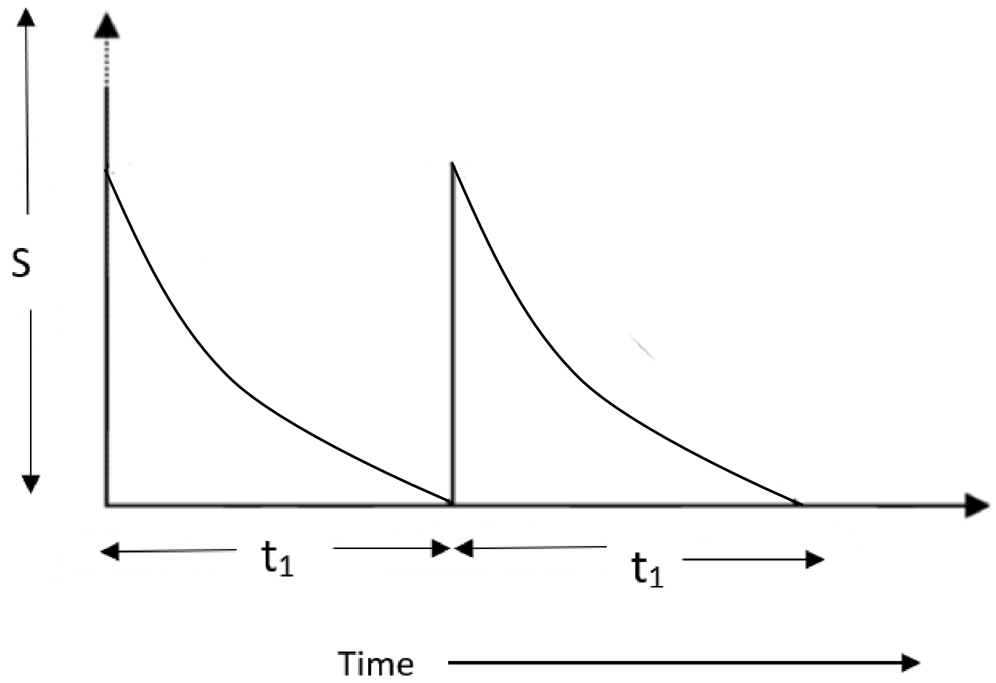

Figure 1: Inventory Level Over Time t_1

In this model, we assumed that items are withdrawn continuously at a constant rate R per unit of time, deterioration with a constant rate and the production rate is infinite.

$$\frac{ds}{dt} + \varphi S = -R , \quad 0 \leq t \leq t_1 \qquad \ldots(1)$$

with boundary condition $S(0) = S_0$ and $S(t_1) = 0$

$$S(t) = \frac{R}{\varphi}(e^{\varphi(t_1 - t)} - 1) \qquad \ldots(2)$$

Using $S(0) = S_0$

$$S_0 = \frac{R}{\varphi}(e^{\varphi t_1} - 1) \quad \ldots(3)$$

The number of units that deteriorated (D) during one cycle is

$$D_0 = S_0 - Rt_1 = \frac{R}{\varphi}(e^{\varphi t_1} - 1) - Rt_1 \quad \ldots(4)$$

Hence, the cost due to deteriorated is given by: -

$$CD_0 = C\left(\frac{R}{\varphi}(e^{\varphi t_1} - 1) - Rt_1\right) \quad \ldots(5)$$

The inventory holding cost is given by: -

$$HC_0 = C_h \int_0^{t_1} S(t)dt$$

$$HC_0 = C_h.\frac{R}{\varphi}\left[\frac{(e^{\varphi t_1} - 1)}{\varphi} - t_1\right] \quad \ldots(6)$$

Safety stock level is given by: -

$$SS = z * \sigma_L \quad \ldots(7)$$

The total Average cost is given by: -

$$X = \frac{1}{t_1}[A + HC_0 + CD_0 + z * \sigma_L * C_h]$$

$$X = \frac{A}{t_1} + C_h \frac{R}{\varphi^2}\left(\frac{(e^{\varphi t_1} - 1)}{t_1}\right) - \frac{C_h R}{\varphi} + \frac{CR}{\varphi}\left(\frac{e^{\varphi t_1} - 1}{t_1}\right) - CR + \frac{z * \sigma_L * C_h}{t_1} \quad \ldots(8)$$

For optimum cost

$$\frac{dX}{dt_1} = 0 \text{ and } \frac{d^2X}{dt_1^2} > 0$$

$$\frac{dX}{dt_1} = -A + \left(\frac{C_h R}{\varphi^2} + \frac{CR}{\varphi}\right)(t_1 \varphi e^{\varphi t_1} - e^{\varphi t_1} + 1) - z * \sigma_L * C_h = 0 \quad \ldots(9)$$

$$\frac{d^2X}{dt_1^2} = t_1 \varphi^2 \left(\frac{C_h R + CR\varphi}{\varphi^2}\right) > 0 \quad \ldots(10)$$

3. Data Collection

The data has been collected through interface and discussion with the ad-hoc staff working with the World Food Program (WFP) vendors in Gwoza local government area, Borno Stae, Northeast Nigeria. Some important information was taken through structural and non-structural interviews of the workers of the vendors and the maintained data of the firm of ordering cost, holding cost, deterioration rate, etc. is also used as the primary source of data. Table 1 shows the monthly and forecast demand for foodstuff for WFP.

Table 1: Monthly Demand and Forecast Demand of Foodstuff

Months	**Total hold Weight (In tonnes)**	**Demand Weight (In tonnes)**	**Forecast Demand (In tonnes)**
January	154	142	146.69
February	330	270	278.92

March	462	351	362.60
April	406	455	470.04
May	366	342	353.30
June	421	411	424.58
July	337	370	382.23
August	235	246	254.13
September	112	119	122.93
October	80	91	94.008
November	59	46	47.520
December	70	62	64.04

Forecast Demand = Forecast Average Monthly Demand*Seasonal Index

Numerical examples

The parameters of the mathematical model are chosen.

A=\$120, C_h=\$2, $R = 146.69$, $C = \$108$, $z = 1.65$; $\sigma_L = 0.1 * R$, $\varphi = 0.001$ in appropriate units. We obtained the optimal value $\boldsymbol{t_1 = 28.96\ days\ TC = \$298.68}$ and $\boldsymbol{Q = 165.89}$ units.

4. Sensitivity analysis:

By adjusting the parameter values in our model and observing the effects on t_1, Q, and TC, we analyzed the impact of variations in Table 2.

Table 2: Impact of Parameter Variations on t_1, Q and TC

Parameters	%	$\boldsymbol{t_1}$	***TC***	***Q***
	-20%	26.44	272.69	153.56
	-10%	27.73	285.98	159.86
A	**0%**	28.96	298.68	165.89
	10%	30.14	310.86	171.67
	20%	31.28	322.58	177.23
	-20%	32.17	268.85	181.61
	-10%	30.44	284.16	173.13
C_h	**0%**	28.96	298.68	165.89
	10%	27.68	312.52	159.61
	20%	26.55	325.78	154.10
	-20%	31.83	262.63	143.95
	-10%	30.27	280.96	155.07
R	**0%**	28.96	298.68	165.89
	10%	27.84	315.87	176.47
	20%	26.88	332.63	186.83
	-20%	29.11	297.13	166.62

φ	**-10%**	29.03	297.91	166.25
	0%	28.96	298.68	165.89
	10%	28.88	299.45	165.53
	20%	28.81	300.21	165.17
C	**-20%**	29.11	297.14	166.62
	-10%	29.03	297.91	166.25
	0%	28.96	298.68	165.89
	10%	28.88	299.44	165.53
	20%	28.81	300.20	165.17

Table 3: Impact of Deterioration Rate and Demand Rate on The Total Cost

φ / **R**	**0.0008**	**0.0009**	**0.001**	**0.0011**	**0.0012**
117.353	261.27	261.95	262.63	263.30	263.98
133.021	280.73	281.46	282.19	282.92	283.64
146.69	297.13	297.91	298.68	299.45	300.21
161.359	314.24	315.06	315.87	316.68	317.49
176.028	330.91	331.77	332.63	333.48	334.34

5. Graphical Analysis

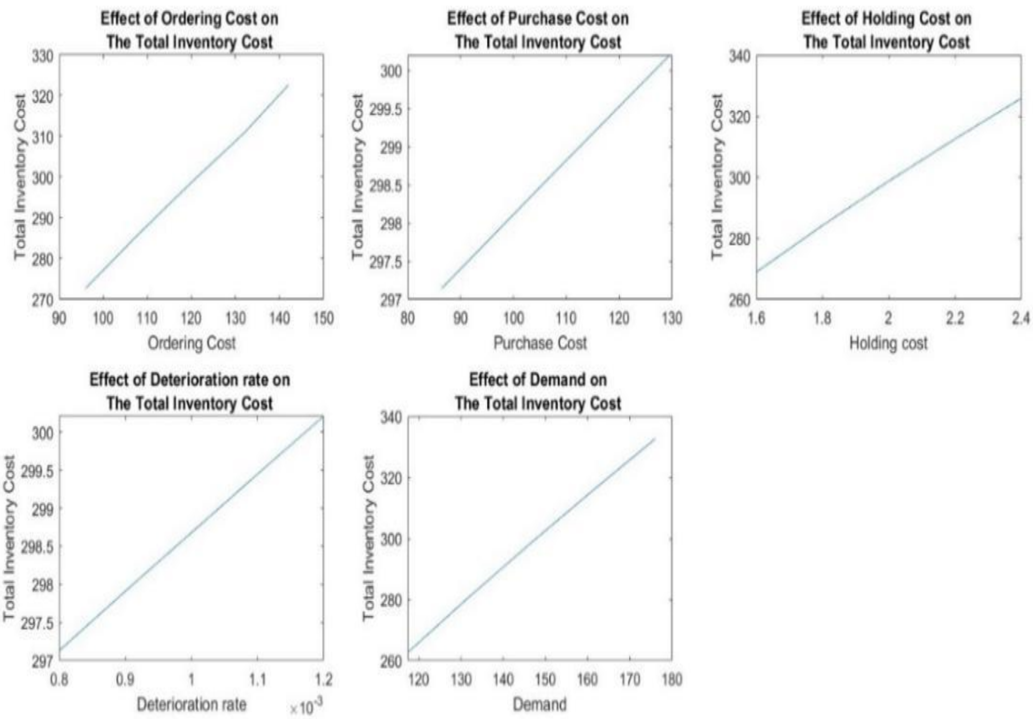

Figure 2: Graphical Analysis and Depiction of the Total Inventory Cost

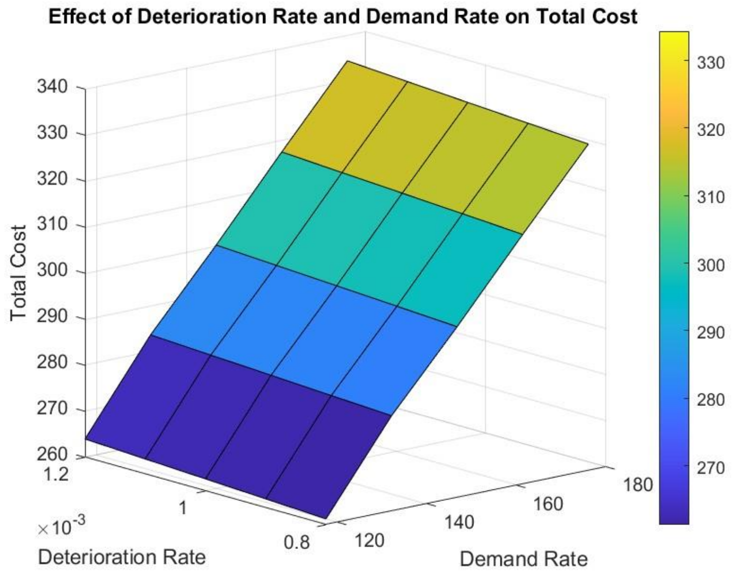

Figure 3: Effect of Deterioration Rate and Demand Rate on The Total Cost

Figure 2 graphically depicts the analyzed impact of parameter variations on total inventory cost. Figure 3 graphically depicts the combined effect of the deterioration rate and demand rate on total inventory cost.

6. Conclusion.

This paper presents an inventory relief supply chain framework implemented by the World Food Program (WFP) in areas controlled by Boko Haram terrorists. The framework aims to optimize the cost of deteriorating items while managing inventory and distribution of relief materials to internally displaced persons (IDPs).

Key findings from the analysis include:

- As A increases by 20%, t_1, TC, and S all increase. A decrease of 20% in A results in lower t_1, TC, and S.
- A 20% increase in C_h results in a decrease in t_1 and S but an increase in TC. A 20% decrease in C_h leads to higher t_1 and S but lower TC.
- A 20% increase in R results in a decrease in $t_1$and an increase in TC and S. A 20% decrease in R results in higher $t_1$and lower TC and S.
- A 20% change in φ results in minimal variations in t_1, TC, and S. This parameter shows less sensitivity than A, Ch, and R.
- A 20% change in C also results in minimal variations in t_1, TC, and Q. This parameter shows similar minimal sensitivity as φ.

Overall, parameters A, C_h, and R significantly impact t_1, TC, and S, while φ and C have minimal effects. A, C_h, and R management is crucial for optimizing inventory performance.

Figure 3 illustrates how the deterioration rate and demand rate impact the total cost. As both rates increase, the total cost rises, highlighting the need to manage these parameters to control inventory expenses.

In conclusion, managing key parameters (A, C_h, and R) is essential for optimizing inventory performance and controlling costs in relief supply chain operations, especially in challenging environments affected by issues such as Boko Haram terrorism.

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