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Inventory Model for Deteriorating Items in Green Supply Chain with Credit Period Dependent Demand

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Abstract

The purpose of this study is to develop optimal inventory model in green supply chain when manufacturer provides permissible delay in payment for a fixed period to the retailer. This scheme is attracting for retailer as he doesn't need to arrange for money initially. It is assumed that demand is directly dependent on credit period. Retailer in turn passes the benefit to customer. Returned products are transported back to manufacturer where they are remanufactured and waste products are recycled. Inventory is assumed to be deteriorating at constant rate. Developed model is solved analytically in crisp and uncertain environments. Numerical observations are provided to authenticate the model.

Keywords: Green Supply Chain, Deterioration, Permissible Delay in Payment, Uncertainty, Inventory, Credit period dependent demand

INTRODUCTION

Permissible delay in payment also called trade credit is a successful business practice where manufacturer provides a delay period in payment to retailer. This is seen in almost all the large economies in the world. It is estimated that 70% of small firms in U.S. employ trade credit. This leads to increase in sales for the manufacturer. For retailer, this is immensely beneficial as it allows retailer to work with lower capital. Also, retailer can earn interest. However, if the payment is not made with in the permissible period, retailer needs to pay interest to manufacturer on the pending amount. Retailer passes this benefit to the customer in order to stimulate demand. It is assumed that retailer will keep credit period lesser than that of manufacturer. Goyal (1985) did initial research on this establishing an EOQ model under permissible delay in payment taking demand as constant. Agarwal and Jaggi (1995) developed an optimal model for deteriorating inventory with permissible delay in payments. It is assumed that interest can be earned on the received revenue during credit period. Huang and Chung (2003) extended Goyal's model incorporating cash discount policy for early payment with trade credit. Jaggi et al. (2008) developed optimal replenishment policies for retailer considering demand dependent on credit period. Agarwal et al. (2016) developed an optimal inventory model for non-instantaneously deteriorating items under trade credit. Unsatisfied demand is assumed to be partially backlogged. Giri and Sharma (2016) studied a two level trade credit financing for inventory system with shortage allowed. It is assumed that customer should pay a part of purchasing cost at the time of ordering and is provided a permissible delay in payment for the rest of the amount. Tiwari et al. (2018) developed a green production system considering supplier offer a trade credit period to buyer.

As green supply chain continues to evolve, various environmental, social and industrial concerns provide new set of opportunities to the researchers for further investigation. In the initial days, we mostly saw theoretical research in this area. Seuring (2013) reviewed various GSCM literature and showed that out of 308 papers published from 1990 to 2010, only 36 were quantitative models. However, in the last few years, more and more conceptual and optimal frameworks have been developed. Messelbeck and Whaley (1999) discussed that health institutions should set example of reducing waste by starting process within themselves and how health care institutions can pull performance requirements through the entire supply chain. Zhu et al. (2008) presented a cross country comparison in automobile industry employing various environmental supply chain management practices. Kannan et al. (2012) developed a mixed integer linear model for transportation and network design with objective of minimizing the carbon footprint and employing reverse logistics. Fahimnia et al. (2015) developed a tactical model to investigate tradeoffs between environment degradation and cost focusing on various aspects that impact environment e.g. carbon emissions, waste generations, energy consumption. Nested Integrated Cross-Entropy method is used to solve the mathematical model and the results are presented with focus on relationship between lean practices and achieving green supply. Saha et al. (2017) developed an inventory model to optimize retailer profit by investing in green operations and preservation technology and optimizing the replenishment time taking deteriorating inventory into consideration. The model is solved using simulated annealing algorithm. Mirghafoori et al. (2017) studied the application of green performance in tile manufacturing industry and proposed a conceptual model with multiple hypothesis using structural equation modeling. They established that agility in supply chain positively impacts organization strategy, financial performance and customer satisfaction. Rani et al. (2018) developed an inventory model for deteriorating products in Green Supply Chain under storage assuming demand from customer to be partially backlogged. Soysal et al. (2018)

discussed the benefits of horizontal collaborate in the inventory routing problem for deterioration, Carbon emissions and logistics and developed a decision support model to address these concerns. Chavoshlou et al. (2019) utilized fuzzy game theory to develop an optimization model in green supply chain. Rani et al. (2019) studied the green supply chain for deteriorating inventory with carbon concerned demand. They developed a crisp model and fuzzy model using triangular fuzzy number assuming demand and deterioration as fuzzy.

Deterioration is a common phenomenon that occurs in a large category of items. This leads to loss of inventory and it can has large impact the overall supply chain thus its impact shouldn't be ignored. Extensive research is conducted in this area and researchers have been continuously working on analyzing its impact accurately. Ghare and Schrader (1963) did the initial research on deterioration taking constant deterioration rate. Covert and Philip (1973) extended the model by assuming weibull deterioration rate. Hariga and Benkherouf (1994) developed optimal and heuristic model assuming constant deterioration. Demand rate is assumed to be exponentially changing. Since then, a large number of researches were done combining deterioration with other important aspect to build inventory models. Bakker et al. (2012) reviewed various researches and provided a comprehensive review of inventory systems with deterioration. Das et al. (2013) developed an integrated model of supplier and retailer with permissible delay in payment for inventory deteriorating at constant rate. Procurement cost is assumed to be linearly dependent on credit period. Ghoreishi et al. (2015) built an inventory model for deteriorating items assuming non-instantaneous deterioration with partial backlogging and permissible delay in payment. Inflation is considered in the model and demand is assumed to be selling price-dependent. Rani et al. (2017) proposed an inventory model for deteriorating items in green supply chain under inflation. Deterioration is assumed to follow two parameter weibull distribution throughout the manufacturing and remanufacturing cycle. Demand of remanufactured products is assumed to be different than that of new products. Hsieh and Dye (2017) studied the effect of reference price into a deteriorating inventory considering demand is dependent on displayed stock level and selling price. Rani et al. (2018) developed an optimal inventory model for deteriorating items in green supply chain assuming non-instantaneous deterioration. Customer is assumed to be environment savvy and learning effect is taken into account.

Most models assume that various supply chain parameters are deterministic. However, due to the complexity of real-world situations and factors involved, parameters typically follows a range of value rather than a single value. Thus it is better to model these parameters as uncertain variables. Lin (2007) proposed uncertainty theory to represent this uncertainty and further enhanced it in Liu (2010). Uncertainty theory works on three fundamental principle: uncertain variables to represent the imprecise parameters, uncertain measure to represent the degree of belief of an event, and uncertain distribution to describe uncertain variables. Various models are developed using these fundamental principles for optimization. Zhang and Peng (2013) studied optimal assignment problem with uncertain profit employing uncertainty theory. Chen et al. (2014) discussed uncertainty method and its applications in evaluating software quality. Zhang et al. (2015) utilized uncertainty theory to model the uncertain multi-modal shortest path problems considering arc travel time and arc travel cost as uncertain variables. Khatua et al. (2017) developed a production inventory model in green supply chain assuming holding cost parameters as uncertain variables.

In this study we develop an optimal inventory model for new and remanufactured products in green supply chain. An integrated model is developed assuming manufacturing and remanufacturing occurring simultaneously and each cycle of remanufacturing having multiple cycles of manufacturing. It is assumed that manufacturer provides a trade credit period to retailer and retailer in turn provides a trade credit period to customers to boost sales. The objective is to minimize total average cost in crisp and uncertain environment.

NOTATIONS

Following parameters are used throughout the model:

θ Deterioration parameter

T Total cycle time including multiple manufacturing and single remanufacturing cycle

Manufacturing parameters:

P_{rM} Production rate parameter

η, Υ Demand rate parameters

t_{M1} Time at which inventory level reaches maximum

t_{M2} Time at which inventory level becomes zero

L Total number of manufacturing cycles in T

$S_{M1}(t)$ Inventory level at time t in the period $0 \le t \le t_{M1}$

$S_{M2}(t)$ Inventory level at time t in the period $t_{M1} \le t \le t_{M2}$

C_{S1} Set up cost parameter

C_{P1} Production cost parameter

C_{H1} Holding cost parameter

C_{D1} Deterioration cost parameter

Remanufacturing parameters:

P_{rR} Reproduction rate parameter

η, Υ Demand rate parameters

t_{R1} Time at which inventory level is maximum

T	Time at which inventory level reaches zero also total cycle time
$S_C(t)$	Collection Inventory level at time t
δ	Returned rate parameter for collected inventory
μ	Recovery rate parameter for collected inventory
$S_{R1}(t)$	Inventory level at time t in the period $0 \le t \le t_{R1}$
$S_{R2}(t)$	Inventory level at time t in the period $t_{R1} \le t \le T$
C_{S2}	Set up cost parameter
C_{P2}	Production cost parameter
C_{D2}	Deterioration cost parameter
C_{H2}	Holding cost parameter

Retailer's parameters

t_B	Time at which inventory reaches zero
$S_B(t)$	Inventory level at time t in the range $0 \le t \le t_B$
D_B	Demand rate parameter
V_B	Number of shipments in one manufacturing cycle
μ_{tC}	Trade credit parameter
t_{PB}	Settlement time for customer
t_{PD}	Settlement time for retailer
C_{OB}	Ordering cost parameter
C_{HB}	Holding cost parameter
C_{DB}	Deterioration cost parameter
C_{PB}	Purchasing cost parameter
S_P	Selling price per unit
E_{I1}	Rate of interest for interest earned
E_{I2}	Rate of interest for interest charged by manufacturer
I_{C2}	Rate of interest for interest charged

Uncertain parameters

$\tilde{\theta}$	Uncertain deterioration parameter
$\tilde{\eta}, \tilde{\gamma}$	Uncertain demand parameters for manufacturing
$\tilde{D}_B$	Uncertain demand parameter for retailer
$\tilde{C}_{H1}$	Uncertain holding cost parameter during manufacturing
$\tilde{C}_{H2}$	Uncertain holding cost parameter during remanufacturing
$\tilde{C}_{HB}$	Uncertain holding cost parameter for retailer
$\tilde{\mu}_{tc}$	Uncertain trade credit parameter

ASSUMPTIONS

Following assumptions are made while developing mathematical model:

- Lead time is negligible.
- Inventory is of single product.
- Manufactured and remanufactured products are of same quality and indistinguishable.
- Deterioration is assumed to be constant.
- Transportation cost is fixed from each plant for all periods and part of ordering cost.
- Products are returned at rate δ which are collected and transported back to manufacturer.
- Returned products are recovered at rate μ while waste product is recycled.
- Various parameters such as demand parameters, deterioration parameter, holding cost parameters are imprecise and are modelled as uncertain variables.
- Manufacturer provide a credit period to retailer t_{PD} and retailer provide credit period to consumer t_{PB} where $t_{PD} > t_{PB}$.

MATHEMATICAL MODEL

In the proposed mathematical model, it is assumed that manufacturing and remanufacturing occur simultaneously. However they have different cycle times. One cycle contains single cycle of remanufacturing and have multiple manufacturing cycles and is represented as T. Remanufactured products are considered as good as new products and have same demand. Deterioration is taken into account throughout the model and is represented by θ.

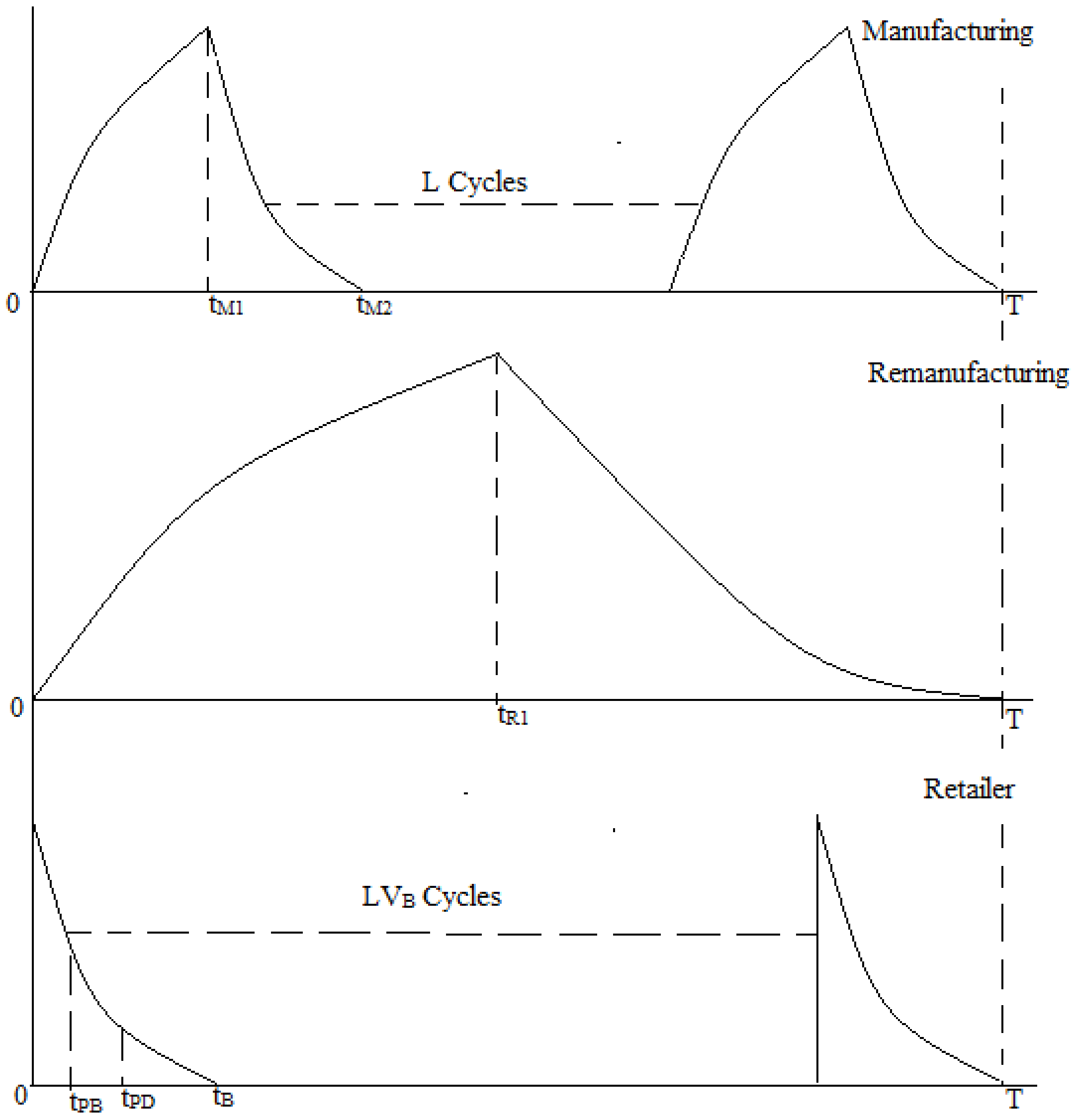

Fig. 1 represents single supply chain cycle including manufacturing and remanufacturing

Manufacturing Cycle:

Production starts a time t=0 and continue till t_{M1}. Production rate is given by PrM. Inventory decreases due to demand η + ϒt and deterioration θ. At t=t_{M1}, enough inventory is accumulated and production is stopped. Accumulated inventory serves demand till t_{M2}. At this time inventory becomes 0 and production cycle starts again.

$$\frac{dS_{M1}(t)}{dt} = P_{rM} - (\eta + \gamma t) - \theta S_{M1}(t) \qquad 0 \le t \le t_{M1} \tag{1}$$

At t = 0; $S_{M1}(t) = 0$ (2)

$$S_{M1}(t) = e^{-\theta t}((P_{rM} - \eta)t - (\gamma - \theta(P_{rM} - \eta))\frac{t^2}{2} - \gamma\theta\frac{t^3}{3}) \tag{3}$$

$$\frac{dS_{M2}(t)}{dt} = -(\eta + \gamma t) - \theta . S_{M2}(t) \qquad t_{M1} \le t \le t_{M2} \tag{4}$$

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At t= t_{M2}; $S_{M2}(t)=0$ (5)

$$S_{M2}(t)=e^{-\theta t}((\eta t_{M2}+(\gamma+\eta\theta)\frac{t_{M2}{}^{2}}{2}+\gamma\theta\frac{t_{M2}{}^{3}}{3})-(\eta t+(\gamma+\eta\theta)\frac{t^{2}}{2}+\gamma\theta\frac{t^{3}}{3})) \tag{6}$$

Assuming L cycles of manufacturing in one overall cycle, t_{M2} is given by:

$$t_{M2}=\frac{T}{L} \tag{7}$$

Manufacturing Costs: Following are the various costs during manufacturing:

Setup Cost:

$(SC)_M = C_{S1}$ (8)

Production Cost:

$$(PC)_M = C_{P1}\int_0^{t_{M1}} P_{rM}\,dt \tag{9}$$

$$= C_{P1}\,P_{rM}\,t_{M1} \tag{10}$$

Holding Cost:

$$(HC)_M = C_{H1}[\int_0^{t_{M1}} S_{M1}(t)\,dt+\int_{t_{M1}}^{t_{M2}} S_{M2}(t)\,dt] \tag{11}$$

$$= C_{H1}\left[\begin{array}{l}(P_{rM}-\eta)\frac{t_{M1}{}^{2}}{2}-(\gamma-\theta(P_{rM}-\eta))\frac{t_{M1}{}^{3}}{2}+\theta(\gamma-3\theta(P_{rM}-\eta))\frac{t_{M1}{}^{4}}{24}+\theta^{2}\gamma\frac{t_{M1}{}^{5}}{15})\\ +(\eta t_{M2}+(\gamma+\eta\theta)\frac{t_{M2}{}^{2}}{2}+\gamma\theta\frac{t_{M2}{}^{3}}{3})(t_{M2}-t_{M1})-(\frac{\eta(t_{M2}{}^{2}-t_{M1}{}^{2})}{2}+(\gamma+\eta\theta)\\ \frac{t_{M2}{}^{3}-t_{M1}{}^{3}}{6}+\gamma\theta\frac{t_{M2}{}^{4}-t_{M1}{}^{4}}{12})-\theta((\eta t_{M2}+(\gamma+\eta\theta)\frac{t_{M2}{}^{2}}{2}+\gamma\theta\frac{t_{M2}{}^{3}}{3})\frac{(t_{M2}{}^{2}-t_{M1}{}^{2})}{2}\\ -\frac{\eta(t_{M2}{}^{3}-t_{M1}{}^{3})}{3}-(\gamma+\eta\theta)\frac{t_{M2}{}^{4}-t_{M1}{}^{4}}{8}-\gamma\theta\frac{(t_{M2}{}^{5}-t_{M1}{}^{5})}{15})\end{array}\right] \tag{12}$$

Deterioration Cost:

$$(DC)_M = C_{D1}[\int_0^{t_{M1}} \theta.S_{M1}(t)\,dt+\int_{t_{M1}}^{t_{M2}} \theta.S_{M2}(t)\,dt] \tag{13}$$

$$= C_{D1}\theta \left[\begin{array}{l} (P_{rM}-\eta)\frac{t_{M1}^{2}}{2}-(\gamma-\theta(P_{rM}-\eta))\frac{t_{M1}^{3}}{2}+\theta(\gamma-3\theta(P_{rM}-\eta))\frac{t_{M1}^{4}}{24}+\theta^{2}\gamma\frac{t_{M1}^{5}}{15}) \\ +(\eta t_{M2}+(\gamma+\eta\theta)\frac{t_{M2}^{2}}{2}+\gamma\theta\frac{t_{M2}^{3}}{3})(t_{M2}-t_{M1})-(\frac{\eta(t_{M2}^{2}-t_{M1}^{2})}{2}+(\gamma+\eta\theta) \\ \frac{t_{M2}^{3}-t_{M1}^{3}}{6}+\gamma\theta\frac{t_{M2}^{4}-t_{M1}^{4}}{12})-\theta((\eta t_{M2}+(\gamma+\eta\theta)\frac{t_{M2}^{2}}{2}+\gamma\theta\frac{t_{M2}^{3}}{3})\frac{(t_{M2}^{2}-t_{M1}^{2})}{2} \\ -\frac{\eta(t_{M2}^{3}-t_{M1}^{3})}{3}-(\gamma+\eta\theta)\frac{t_{M2}^{4}-t_{M1}^{4}}{8}-\gamma\theta\frac{(t_{M2}^{5}-t_{M1}^{5})}{15}) \end{array} \right] \quad (14)$$

Remanufacturing Cycle:

Collection happens throughout the cycle during manufacturing and remanufacturing. Used and returned products are collected and transported back to manufacturer where they are remanufactured. Considering customer demand as $D_B + \mu_{tC}\, t_{PB}$ and δ as returned rate, collected inventory at time t is given by:

$$S_C(t) = \delta(D_B + \mu_{tc} t_{PB}) \quad (15)$$

Manufacturer utilize this collected inventory to remanufacture products while recycling wastes. Reproduction starts at time t = 0 and continue till t_{R1}. Inventory reduced due to demand η + ϒt and deterioration θ. At t_{R1}, enough inventory is accumulated and production is stopped. Inventory reduces due to demand and deterioration until time T when inventory becomes 0.

$$\frac{dS_{R1}(t)}{dt} = P_{rR} - (\eta + \gamma t) - \theta.S_{R1}(t) \qquad 0 \le t \le t_{R1} \quad (16)$$

At t=0; $S_{R1}(t) = 0$ (17)

$$S_{R1}(t) = e^{-\theta t}((P_{rR}-\eta)t - (\gamma - \theta(P_{rR}-\eta))\frac{t^2}{2} - \gamma\theta\frac{t^3}{3}) \quad (18)$$

$$\frac{dS_{R2}(t)}{dt} = -(\eta + \gamma t) - \theta.S_{R2}(t) \qquad t_{R1} \le t \le T \quad (19)$$

At t = T; $S_{R2}(t) = 0$ (20)

$$S_{R2}(t) = e^{-\theta t}((\eta T + (\gamma+\eta\theta)\frac{T^2}{2} + \gamma\theta\frac{T^3}{3}) - (\eta t + (\gamma+\eta\theta)\frac{t^2}{2} + \gamma\theta\frac{t^3}{3})) \quad (21)$$

Remanufacturing Costs: Following are the costs during remanufacturing:

Setup Cost:

$(SC)_R = C_{S2}$ (22)

Production Cost:

$$(PC)_R = C_{P2}\int_0^{t_{R1}} P_{rR}\,dt \tag{23}$$

$$= C_{P2}\,P_{rR}\,t_{R1} \tag{24}$$

Holding Cost:

$$(HC)_R = C_{H2}[\int_0^{t_{R1}} S_{R1}(t)\,dt + \int_{t_{R1}}^{T} S_{R2}(t)\,dt] \tag{25}$$

$$= C_{H2}\begin{bmatrix} (P_{rR}-\eta)\frac{t_{R1}^{\ 2}}{2} - (\gamma-\theta(P_{rR}-\eta))\frac{t_{R1}^{\ 3}}{6} - \theta\gamma\frac{t_{R1}^{\ 4}}{12} - \theta((P_{rR}-\eta)\frac{t_{R1}^{\ 3}}{3} - \\ (\gamma-\theta(P_{rR}-\eta))\frac{t_{R1}^{\ 4}}{8} - \theta\gamma\frac{t_{R1}^{\ 5}}{15}) + (\eta T + (\gamma+\eta\theta)\frac{T^2}{2} + \gamma\theta\frac{T^3}{3})(T-t_{R1}) \\ -(\frac{\eta(T^2-t_{R1}^{\ 2})}{2} + (\gamma+\eta\theta)\frac{T^3-t_{R1}^{\ 3}}{6} + \gamma\theta\frac{T^4-t_{R1}^{\ 4}}{12}) - \theta((\eta T + (\gamma+\eta\theta) \\ \frac{T^2}{2} + \gamma\theta\frac{T^3}{3})\frac{(T^2-t_{R1}^{\ 2})}{2} - \frac{\eta(T^3-t_{R1}^{\ 3})}{3} - (\gamma+\eta\theta)\frac{T^4-t_{R1}^{\ 4}}{8} - \gamma\theta\frac{(T^5-t_{R1}^{\ 5})}{15}) \end{bmatrix} \tag{26}$$

Deterioration Cost:

$$(DC)_R = C_{D2}[\int_0^{t_{R1}} \theta.S_{R1}(t)\,dt + \int_{t_{R1}}^{T} \theta.S_{R2}(t)\,dt] \tag{27}$$

$$= C_{D2}\theta\begin{bmatrix} (P_{rR}-\eta)\frac{t_{R1}^{\ 2}}{2} - (\gamma-\theta(P_{rR}-\eta))\frac{t_{R1}^{\ 3}}{6} - \theta\gamma\frac{t_{R1}^{\ 4}}{12} - \theta((P_{rR}-\eta)\frac{t_{R1}^{\ 3}}{3} - \\ (\gamma-\theta(P_{rR}-\eta))\frac{t_{R1}^{\ 4}}{8} - \theta\gamma\frac{t_{R1}^{\ 5}}{15}) + (\eta T + (\gamma+\eta\theta)\frac{T^2}{2} + \gamma\theta\frac{T^3}{3})(T-t_{R1}) \\ -(\frac{\eta(T^2-t_{R1}^{\ 2})}{2} + (\gamma+\eta\theta)\frac{T^3-t_{R1}^{\ 3}}{6} + \gamma\theta\frac{T^4-t_{R1}^{\ 4}}{12}) - \theta((\eta T + (\gamma+\eta\theta) \\ \frac{T^2}{2} + \gamma\theta\frac{T^3}{3})\frac{(T^2-t_{R1}^{\ 2})}{2} - \frac{\eta(T^3-t_{R1}^{\ 3})}{3} - (\gamma+\eta\theta)\frac{T^4-t_{R1}^{\ 4}}{8} - \gamma\theta\frac{(T^5-t_{R1}^{\ 5})}{15}) \end{bmatrix} \tag{28}$$

Collection Cost:

$$(CC)_R = C_C(\int_0^{T} S_C(t)\,dt) \tag{29}$$

$$= C_C\delta(D_B + \mu_{tc}t_{PB})T \tag{30}$$

Retailer Cycle:

Each manufacturing and remanufacturing cycle has multiple retailer cycles. We consider that manufacturer allows a permissible delay in retailer to make payment for time t_{PD}. This is beneficial for retailer as he doesn't need to arrange credit upfront and he can earn interest on this. Retailer also provides credit period to customer with time t_{PB} where $t_{PB} < t_{PD}$. This also results in increase in demand from customer. Let's assume overall customer demand is $D_B + \mu_{tC}\, t_{PB}$. Retailer receives ordered inventory at t = 0. Inventory decreases due to demand and deterioration θ until t_B when inventory reaches 0.

$$\frac{dS_B(t)}{dt} = -(D_B + \mu_{tc} t_{PB}) - \theta . S_B(t) \qquad 0 \le t \le t_B \tag{31}$$

At t = t_B, $S_B(t) = 0$ (32)

$$S_B(t) = e^{-\theta t}(D_B + \mu_{tc} t_{PB})(t_B - t)(1 + \frac{\theta}{2}(t_B + t)) \tag{33}$$

Assuming one manufacturing cycle contains V_B retailer's cycle, cycle time is given by:

$$t_B = \frac{T}{LV_B} \tag{34}$$

Retailer's Cost: Following are the various retailer's cost

Ordering Cost:

$(OC)_{RE} = C_{OB}$ (35)

Purchasing Cost:

$(PC)_{RE} = C_{PB}\, S_B(t = 0)$ (36)

$$= C_{PB}(D_B + \mu_{tc} t_{PB})(t_B + \theta \frac{t_B^{\ 2}}{2}) \tag{37}$$

Holding Cost:

$(HC)_{RE} = C_{HB} \int_0^{t_B} S_B(t)\, dt$ (38)

$$= C_{HB}\left[(D_B + \mu_{tc} t_{PB})((t_B + \theta \frac{t_B^{\ 2}}{2})(t_B - \theta \frac{t_B^{\ 2}}{2}) - (\frac{t_B^{\ 2}}{2} + \theta \frac{t_B^{\ 3}}{6}) + \theta \frac{t_B^{\ 3}}{3} + \theta^2 \frac{t_B^{\ 4}}{8})) \right] \tag{39}$$

Deterioration Cost:

$(DC)_{RE} = C_{DB} \int_0^{t_B} \theta\, S_B(t)\, dt$ (40)

$$= C_{DB}\theta \left[(D_B + \mu_{tc} t_{PB})((t_B + \theta \frac{t_B^{\ 2}}{2})t_B - (\frac{t_B^{\ 2}}{2} + \theta \frac{t_B^{\ 3}}{6}) - \theta((t_B + \theta \frac{t_B^{\ 2}}{2})\frac{t_B^{\ 2}}{2} - \frac{t_B^{\ 3}}{3} - \theta \frac{t_B^{\ 4}}{8})) \right] \tag{41}$$

With regard to interest earned and interest charged, two cases arises:

Case 1: When t_{PD} >= t_B

In this case, trade credit period is higher than or equal to that of cycle time. So, interest charged will be 0 while retailer can earn interest throughout the cycle. Taking t_{PB} is the credit time for end customer:

$(IC)_{RE} = 0$ (42)

$$(IE)_{RE} = S_p E_{I1}\left(\int_{t_{PB}}^{t_B} (D_B + \mu_{tc} t_{PB})\, t\, dt + (t_{PD} - t_B)\int_{t_{PB}}^{t_B} (D_B + \mu_{tc} t_{PB})\, dt\right) \tag{43}$$

$$= S_p E_{I1}(D_B + \mu_{tc} t_{PB})(t_B - t_{PB})\frac{(t_{PB} + 2t_{PD} - t_B)}{2} \tag{44}$$

Case 2: When $t_{PD} < t_B$

In this case, retailer doesn't pay any charge till t_{PD} but will have to pay interest for the rest of the time.

$$(IC)_{RE} = P_P I_{C2} S_B(t)(t_B - t_{PD}) \tag{45}$$

$$= P_P I_{C2}(D_B + \mu_{tc} t_{PB})(t_B + \frac{\theta t_B{}^2}{2})(t_B - t_{PD}) \tag{46}$$

$$(IE)_{RE} = S_p E_{I2}\int_{t_{PB}}^{t_{PD}} (D_B + \mu_{tc} t_{PB})\, t\, dt \tag{47}$$

$$= S_p E_{I2}(D_B + \mu_{tc} t_{PB})\frac{(t_{PD}{}^2 - t_{PB}{}^2)}{2} \tag{48}$$

Total Average Cost: Total average cost during manufacturing and remanufacturing is given by:

$$(TAC)_{MRB} = \frac{L}{T}(SC + PC + HC + DC)_M + \frac{1}{T}(SC + PC + HC + DC + CC)_R + \frac{1}{t_B}(OC + PC + HC + DC + IC - IE)_{RE} \tag{49}$$

$(TAC)_{MRB}$ is minimum provided:

$$\frac{\partial (TAC)_{MRB}}{\partial t_{M1}} = 0, \frac{\partial (TAC)_{MRB}}{\partial t_{R1}} = 0, \frac{\partial (TAC)_{MRB}}{\partial T} = 0 \tag{50}$$

And following conditions are satisfied for Hessian Matrix:

$$\begin{pmatrix} \frac{\partial^2 (TAC)_{MRB}}{\partial t_{M1}{}^2} & \frac{\partial^2 (TAC)_{MRB}}{\partial t_{M1}\partial t_{R1}} & \frac{\partial^2 (TAC)_{MRB}}{\partial T \partial t_{M1}} \\ \frac{\partial^2 (TAC)_{MRB}}{\partial t_{M1}\partial t_{R1}} & \frac{\partial^2 (TAC)_{MRB}}{\partial t_{R1}{}^2} & \frac{\partial^2 (TAC)_{MRB}}{\partial t_{R1}\partial T} \\ \frac{\partial^2 (TAC)_{MRB}}{\partial T \partial t_{M1}} & \frac{\partial^2 (TAC)_{MRB}}{\partial t_{R1}\partial T} & \frac{\partial^2 (TAC)_{MRB}}{\partial T^2} \end{pmatrix} \tag{51}$$

Second Derivative $D_1 = \frac{\partial^2 (TAC)_{MRB}}{\partial t_{M1}^2} > 0$ (53)

Minor $D_2 > 0$ where $D_2 = \begin{vmatrix} \frac{\partial^2 (TAC)_{MRB}}{\partial t_{M1}^2} & \frac{\partial^2 (TAC)_{MRB}}{\partial t_{M1} \partial t_{R1}} \\ \frac{\partial^2 (TAC)_{MRB}}{\partial t_{M1} \partial t_{R1}} & \frac{\partial^2 (TAC)_{MRB}}{\partial t_{R1}^2} \end{vmatrix}$ (54)

Minor $D_3 > 0$ where $D_3 = \begin{vmatrix} \frac{\partial^2 (TAC)_{MRB}}{\partial t_{M1}^2} & \frac{\partial^2 (TAC)_{MRB}}{\partial t_{M1} \partial t_{R1}} & \frac{\partial^2 (TAC)_{MRB}}{\partial T \partial t_{M1}} \\ \frac{\partial^2 (TAC)_{MRB}}{\partial t_{M1} \partial t_{R1}} & \frac{\partial^2 (TAC)_{MRB}}{\partial t_{R1}^2} & \frac{\partial^2 (TAC)_{MRB}}{\partial t_{R1} \partial T} \\ \frac{\partial^2 (TAC)_{MRB}}{\partial T \partial t_{M1}} & \frac{\partial^2 (TAC)_{MRB}}{\partial t_{R1} \partial T} & \frac{\partial^2 (TAC)_{MRB}}{\partial T^2} \end{vmatrix}$ (55)

Numerical Solution:

Using Mathematica to solve above equations taking appropriate values for parameters:

$\eta = 5$, $Y = 0.2$, $\theta = 0.03$, $C_{S1} = 5$, $C_{P1} = 25$, $C_{H1} = 20$, $C_{D1} = 10$, $P_{rM} = 25$, $L = 3$, $P_{rR} = 5$, $\delta = 0.4$, $C_C = 100$, $C_{S2} = 20$, $C_{H2} = 20$, $C_{P2} = 40$, $C_{D2} = 10$, $D_B = 4$, $\mu_{tc} = 0.05$, $C_{OB} = 3$, $C_{PB} = 2$, $C_{HB} = 20$, $C_{DB} = 10$, $S_P = 10$, $P_P = 8$, $I_{C2} = 0.1$, $E_{I1} = 0.01$, $E_{I2} = 0.01$, $V_B = 2$

Case 1: $t_{PD} >= t_B$

Taking: $t_{PB} = 1$, $t_{PD} = 2$

$(TAC)_{MRB} = 1319.76$ where $t_{M1} = 3.41103$, $t_{R1} = 32.7271$, $T = 45.7232$

And

$D_1 = \frac{\partial^2 (TAC)_{MRB}}{\partial t_{M1}^2} = 34.32 > 0$

$D_2 = \frac{\partial^2 (TAC)_{MRB}}{\partial t_{M1}^2} \frac{\partial^2 (TAC)_{MRB}}{\partial t_{R1}^2} - \left(\frac{\partial^2 (TAC)_{MRB}}{\partial t_{M1} \partial t_{R1}}\right)^2$

$= 34.32 * 7.29 - 0 = 250.19 > 0$

$D_3 = \frac{\partial^2 (TAC)_{MRB}}{\partial t_{M1}^2} \left(\frac{\partial^2 (TAC)_{MRB}}{\partial t_{R1}^2} \frac{\partial^2 (TAC)_{MRB}}{\partial T^2} - \left(\frac{\partial^2 (TAC)_{MRB}}{\partial t_{R1} \partial T}\right)^2\right) - \frac{\partial^2 (TAC)_{MRB}}{\partial t_{M1} \partial t_{R1}} \left(\frac{\partial^2 (TAC)_{MRB}}{\partial t_{M1} \partial t_{R1}} \frac{\partial^2 (TAC)_{MRB}}{\partial T^2} - \frac{\partial^2 (TAC)_{MRB}}{\partial t_{R1} \partial T} \frac{\partial^2 (TAC)_{MRB}}{\partial T \partial t_{M1}}\right) + \frac{\partial^2 (TAC)_{MRB}}{\partial T \partial t_{M1}} \left(\frac{\partial^2 (TAC)_{MRB}}{\partial t_{M1} \partial t_{R1}} \frac{\partial^2 (TAC)_{MRB}}{\partial t_{R1} \partial T} - \frac{\partial^2 (TAC)_{MRB}}{\partial t_{R1}^2} \frac{\partial^2 (TAC)_{MRB}}{\partial T \partial t_{M1}}\right)$

$= 34.32[7.29 * 4.43 - 0.27 * 0.27] - 0 + (-4.67)(-7.32 * - 4.67) = 961.223 > 0$

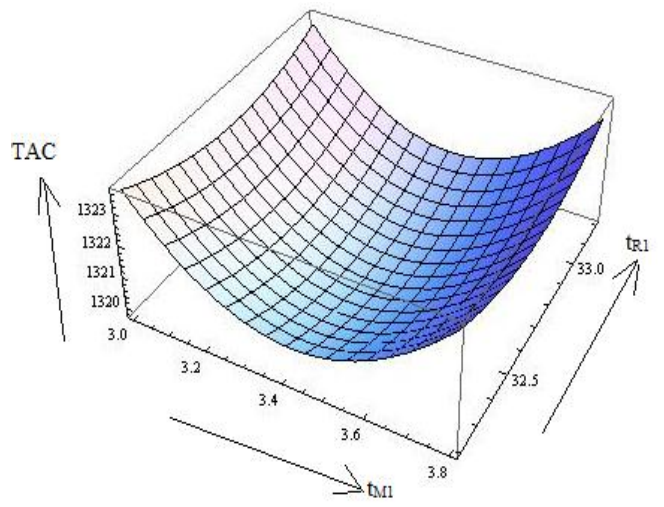

Fig.2 represents convexity of total average cost for t_{M1} and t_{R1}

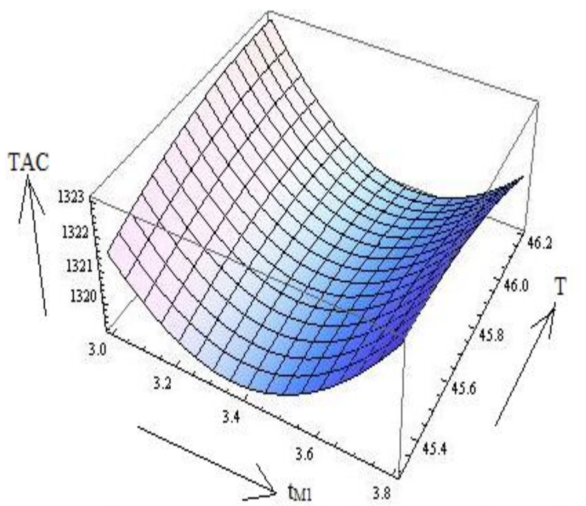

Fig.3 represent convexity of total average cost for t_{M1} and T

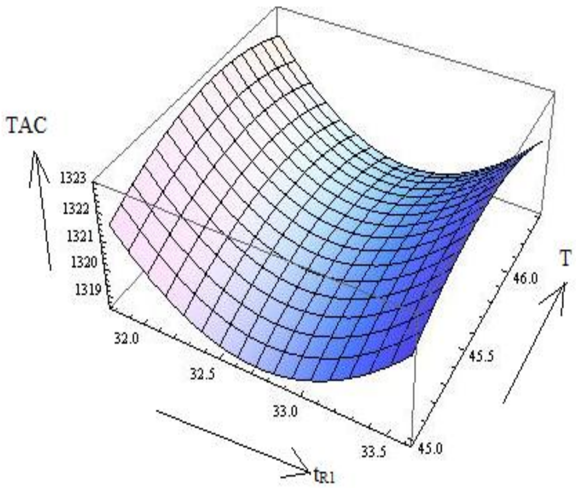

Fig. 4 represents convexity of total average cost for t_{R1} and T

Case 2: $t_{PD} < t_B$

Taking: $t_{PB} = 0.1$, $t_{PD} = 0.2$

$(TAC)_{MRB} = 1340.21$ where $t_{M1} = 3.42526$, $t_{R1} = 32.7309$, $T = 45.8276$

With

$D_1 = 34.24 > 0$

$D_2 = 34.24 * 7.32 = 250.637 > 0$

$D_3 = 34.24(7.32 * 4.53 – (-0.26 * -0.26)) – 0 + (-4.66)(0 – (-4.66 * 7.32) = 974.112 > 0$

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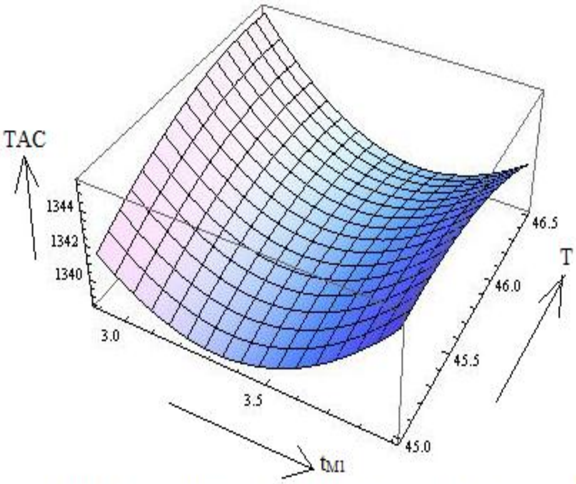

Fig. 5 represents convexity of Total Average Cost for t_{M1} and T

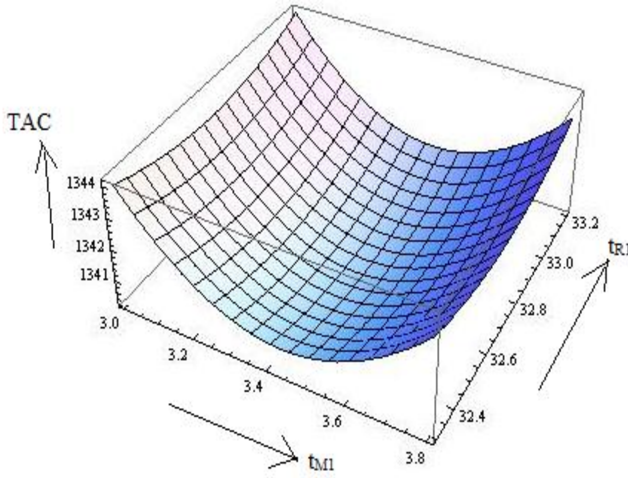

Fig. 6 represent convexity of Total Average Cost for t_{M1} and t_{R1}

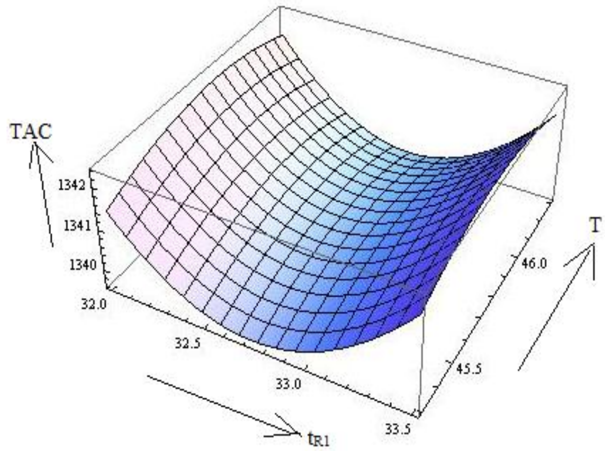

Fig. 7 represents convexity of Total Average Cost for t_{R1} and T

Uncertainty Theory:
In the crisp model, we assumed that various parameters such as demand, deterioration, cost parameters etc. are precisely known. However, in the real world, these parameters depend on various external factors and can't be accurately determined. To deal with this uncertainty, uncertainty theory was proposed by Liu that revolves around three fundamental concepts. Uncertain measure to measure degree of belief of an event. Uncertain variables to represent parameters with imprecise value and uncertain distribution to describe uncertain variables. In this model we consider deterioration parameter θ, demand parameters η, Y, D_B, holding cost parameters C_{H1}, C_{H2}, C_{HB} and trade credit parameter μ_{tc} as uncertain variables.

Following are the definitions used to represent uncertain model:
Uncertain Measure: Let Γ be a non-empty set and ζ be σ algebra over Γ. Then each element Λ ϵ ζ is called an event and set function N is called an uncertain measure if it satisfies following:

I. Normality: $N\{\Gamma\}=1$ for the universal set Γ

II. Duality: $N\{\Lambda\}+N\{\Lambda^c\}=1$ = 1 for any event Λ

III. Subadditivity: $N\left\{\bigcup_{i=1}^{\infty}\Lambda_i\right\}\le\sum_{i=1}^{\infty}\{\Lambda_i\}$ for every countable space of events Λ_1, Λ_2…

IV. Product: $N\left\{\prod_{k=1}^{\infty}\Lambda_k \le\right\}\bigwedge_{k=1}^{\infty}N\{\Lambda_k\}$ where (Γ_k, ζ_k, N_k) is the uncertainty space and Λ_k are arbitrary chosen events from ζ_k for k = 1, 2…

Uncertain Variable: An uncertain variable is defined as a measurable function ξ from an uncertainty space (Γ, ς, N) to the set of real numbers such that {ξ ϵ B} for any Borel set B of real numbers.

$$\{\xi\in B\}=\{y\in\Gamma\mid\xi(y)\in B\}$$

Uncertain Distribution: The uncertainty distribution ϕ: R -> [0, 1] of ξ is defined as

$$\phi(x)=N\{\xi\le x\}$$

And the expected value of uncertain variable is given by:

$$E|\xi| = \int_0^{\infty} N\{\xi \geq x\}dx - \int_{-\infty}^{0} N\{\xi \leq x\}dx$$

Uncertain Variable Characteristics: An uncertain variable exhibits following characteristics:

I. Inverse Function: For an uncertain variable ξ with regular distribution ϕ(x), the inverse function $\phi^{-1}(x)$ is called inverse uncertain distribution such that:

$$E|\xi| = \int_0^1 \phi^{-1}(x)dx$$

II. Independent: The uncertain variable $\xi_1, \xi_2\ldots$ are said to be independent if:

$$N\left\{\bigcup_{i=1}^{n}\{\xi_i \in B_i\}\right\} = \bigwedge_{i=1}^{n} N\{\xi_i \in B_i\}$$

III. Zigzag: Uncertain variable ξ is called zigzag if it has zigzag uncertainty distribution:

$$\phi(x) = \begin{cases} 0 & ; x \leq a \\ \dfrac{(x-a)}{2(b-a)} & ; a \leq x \leq b \\ \dfrac{(x+c-2b)}{2(c-b)} & ; b \leq x \leq c \\ 1 & ; x \geq c \end{cases}$$

And ξ has expected value: $E|\xi| = \dfrac{a+2b+c}{4}$

Zigzag Uncertain Variable Characteristics: A zigzag uncertain variable has following characteristics:

i. Additivity: Assuming ξ_1, ξ_2 are independent zigzag uncertain variables $Z(a_1, b_1, c_1)$ and $Z(a_2, b_2, c_2)$ respectively than the sum($\xi_1 + \xi_2$) is also zigzag uncertain variable such that:

$$Z(a_1,b_1,c_1) + Z(a_2,b_2,c_2) = Z(a_1+a_2, b_1+b_2, c_1+c_2)$$

ii. Multiplicity: The product of zigzag uncertain variable Z(a, b, c) and scalar number k where k > 0 is also zigzag uncertain variable such that:

$$k\,Z(a,b,c) = Z(ka,kb,kc)$$

We consider following parameters as uncertain variables:

$\tilde{\theta} = (\theta_1, \theta_2, \theta_3)$ (56)

$\tilde{\eta} = (\eta_1, \eta_2, \eta_3)$ (57)

$\tilde{\gamma} = (\gamma_1, \gamma_2, \gamma_3)$ (58)

$\tilde{D}_B = (D_{B1}, D_{B2}, D_{B3})$ (59)

$\tilde{C}_{H1} = (C_{H11}, C_{H12}, C_{H13})$ (60)

$\tilde{C}_{H2} = (C_{H21}, C_{H22}, C_{H23})$ (61)

$\tilde{C}_{HB} = (C_{HB1}, C_{HB2}, C_{HB3})$ (62)

$\tilde{\mu}_{tc} = (\mu_{tc1}, \mu_{tc2}, \mu_{tc3})$ (63)

And corresponding expected values are:

$$E[\theta] = \frac{\theta_1 + 2\theta_2 + \theta_3}{4} \quad (64)$$

$$E[\eta] = \frac{\eta_1 + 2\eta_2 + \eta_3}{4} \quad (65)$$

$$E[\gamma] = \frac{\gamma_1 + 2\gamma_2 + \gamma_3}{4} \quad (66)$$

$$E[C_{H1}] = \frac{C_{H11} + 2C_{H12} + C_{H13}}{4} \quad (67)$$

$$E[C_{H2}] = \frac{C_{H21} + 2C_{H22} + C_{H33}}{4} \quad (68)$$

$$E[D_B] = \frac{D_{B1} + 2D_{B2} + D_{B3}}{4} \quad (69)$$

$$E[\mu_{tc}] = \frac{\mu_{tc1} + 2\mu_{tc2} + \mu_{tc3}}{4} \quad (70)$$

$$E[C_{HB}] = \frac{C_{HB1} + 2C_{HB2} + C_{HB3}}{4} \quad (71)$$

Numerical Solution:

Taking appropriate values for input parameters:
$\eta_1 = 4$, $\eta_2 = 5$, $\eta_3 = 6.5$, $Y_1 = 0.15$, $Y_2 = 0.2$, $Y_3 = 0.3$, $\theta = 0.02$, $\theta = 0.03$, $\theta = 0.045$, $C_{S1} = 5$, $C_{P1} = 25$, $C_{H11} = 15$, $C_{H12} = 20$, $C_{H13} = 26$, $C_{D1} = 10$, $P_{rM} = 25$, $L = 3$, $P_{rR} = 5$, $\delta = 0.4$, $C_C = 100$, $C_{S2} = 20$, $C_{H21} = 17$, $C_{H22} = 20$, $C_{H23} = 25$, $C_{P2} = 40$, $C_{D2} = 10$, $D_{B1} = 2.8$, $D_{B2} = 4$, $D_{B3} = 5$, $\mu_{tc1} = 0.042$, $\mu_{tc2} = 0.05$, $\mu_{tc3} = 0.06$, $C_{OB} = 3$, $C_{PB} = 2$, $C_{HB1} = 15$, $C_{HB2} = 20$, $C_{HB3} = 24$, $C_{DB} = 10$, $S_P = 10$, $P_P = 8$, $I_{C2} = 0.1$, $E_{I1} = 0.01$, $E_{I2} = 0.01$, $V_B = 2$

Case 1: $t_{PD} >= t_B$
Taking: $t_{PB} = 1$, $t_{PD} = 2$
$(TAC)_{MRB} = 1274.19$ where $t_{M1} = 3.32158$, $t_{R1} = 31.4223$, $T = 43.7582$
With
$D_1 = 36.36 > 0$
$D_2 = 36.36 * 7.99 = 290.516 > 0$
$D_3 = 36.36(7.99 * 4.84 - (-0.29 * -0.29)) - 0 + (-5.04)(0 - (-5.04 * 7.99)) = 1200.08 > 0$

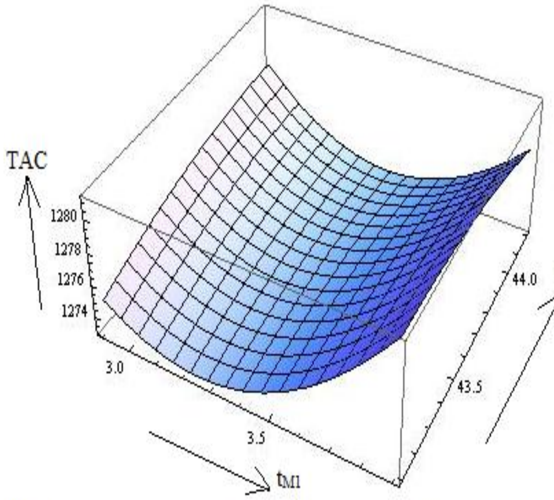

Fig. 8 represents convexity of Total Average Cost for t_{M1} and T in uncertain environment

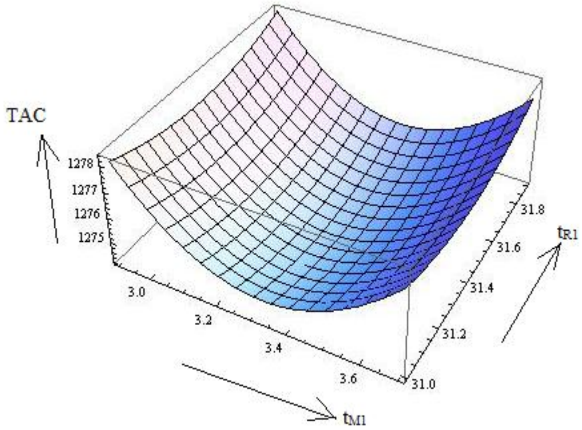

Fig.9 represents convexity of Total Average Cost for t_{M1} and t_{R1} in uncertain environment

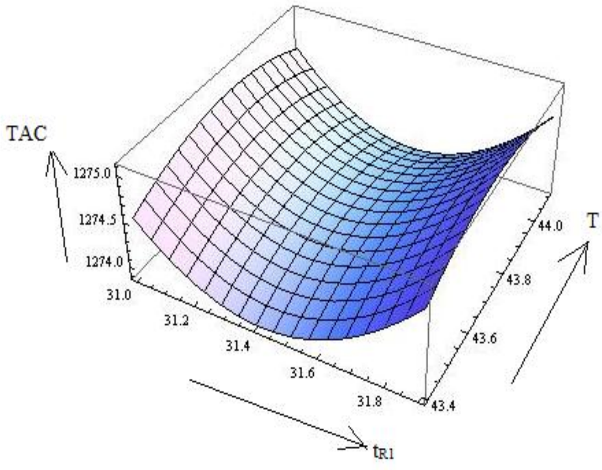

Fig. 10 represents convexity of total average cost for t_{R1} and T in uncertain environment

Case 2: $t_{PD} < t_B$

Taking: $t_{PB} = 0.1$, $t_{PD} = 0.2$

$(TAC)_{MRB} = 1292.62$ where $t_{M1} = 3.33674$, $t_{R1} = 31.4262$, $T = 43.8675$

With

$D_1 = 36.27 > 0$

$D_2 = 36.27 * 8.03 = 291.248 > 0$

$D_3 = 36.27(8.03 * 4.90 – (-0.29 * -0.29)) – 0 + (-5.031) (0 – (-8.03 * 5.031)) = 1220.86 > 0$

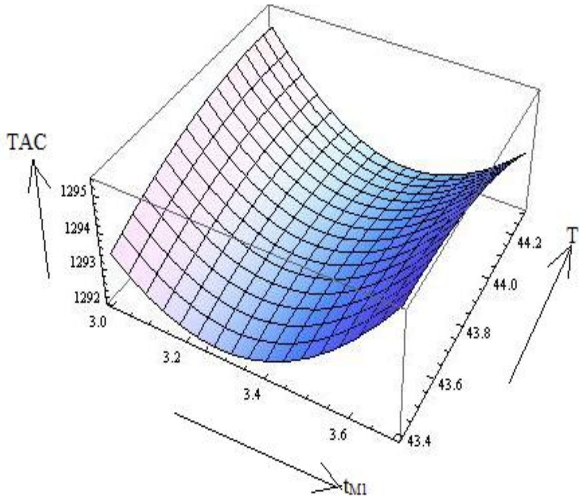

Fig. 11 represents convexity of total average cost for t_{M1} and T in uncertain environment

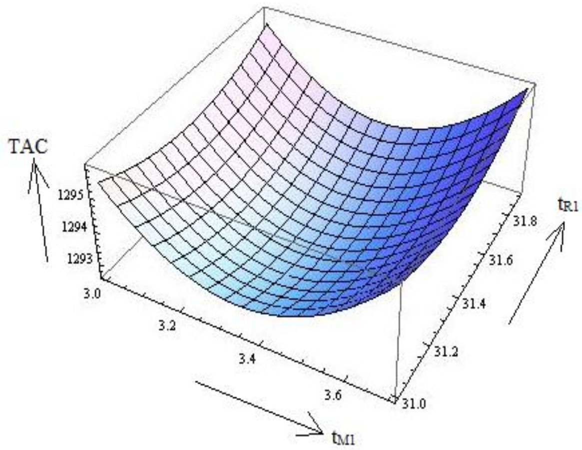

Fig. 12 represents convexity of total average cost for t_{M1} and t_{R1} in uncertain environment

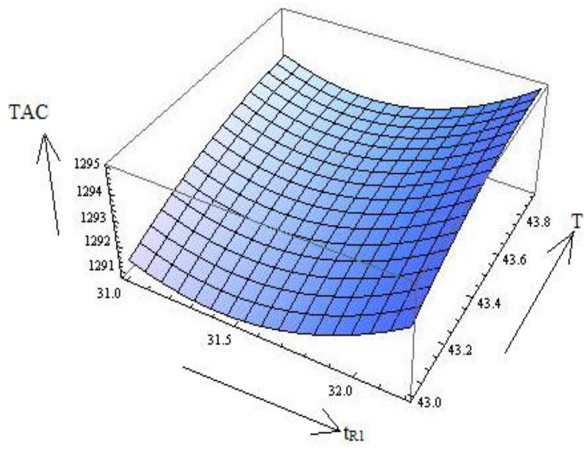

Fig. 13 represents convexity of total average cost for t_{R1} and T in uncertain environment

CONCLUSION

In the present study, we developed an integrated model in green supply chain with simultaneous manufacturing and remanufacturing. The model considers green manufacturing, green design and green operations throughout the supply chain. The inventory is considered to be deteriorating in nature deteriorating at a constant rate. It is assumed that retailer collects the used and returned inventory from where it is manufacturer responsibility to transport back to his manufacturing unit. Collected products are then inspected and reusable parts are separated out from which new products are remanufactured while recycling waste. It is assumed that remanufactured products are as good as new products.

Trade credit is the fundamental concept used in supply chain throughout the world and yet most of the study seems to ignore it. In this study, we consider that manufacturer provides a permissible delay in payment to retailer and retailer also provides a trade credit period to the customer. It has been found that this not only increases the ease of trade in business which is difficult to quantify but also it increases the sale of the product. In the study, it is considered that demand is proportional to the credit period provided. The proposed model is solved in a crisp way taking all the parameters are precisely known. However, this is seldom true. To account for the non-determinism and impreciseness of the parameters, we utilize uncertainty theory where parameters are modeled as uncertain variables and the model is solved using uncertain theory.

Given the realistic nature of this model, this model can serve as a useful input in optimizing existing supply chain as well as transforming existing supply chains to green supply chain. Model can also be utilized by research scholars in their study in this area. The model can be further extended by incorporating some more real-life scenarios such as inflation, seasoning, shortages etc.

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Conflict of Interest:

The authors declare that they have no conflict of interest.

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