A Closed Loop Supply Chain Inventory Model for the Deteriorating Items with JIT Implementation

S. R. Singh and Neha Saxena

Abstract In the past recent years, a growing environmental consciousness has been shaping the way society looks on green. Society's attitude towards environmental issues has been changing and hence recoverable product environments are becoming an increasingly important segment of the overall push in industry. We have proposed a model for the design of a closed loop supply chain with green components. We have investigated a joint economic production quantity model for a single vendor, single buyer system considering lot-splitting. The effect of deterioration is taken into consideration. Here we have assumed that the vendor fulfils the buyer's demand with the produced and remanufactured units, where the remanufactured items are considered as good as those of new items. Mathematical and numerical analysis are presented to describe the situation.

Keywords Inventory model · Production · Remanufacturing · Deterioration · JIT implementation

1 Introduction

Owing to increased public concern about the environment, most developed countries have made legislations, mandating manufacturers and importers to take back used products at the end of their useful lives. Consumers can now return goods within warranty period as part of the after-sales service if the products fail to meet their needs or when the products have reached the end of their useful lives.

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The returned products may then be refurbished or remanufactured to extend their periods of usage or recycled to recapture value. For sustainable development, a good supply chain strategy enables manufacturing plant to rescue and recover many parts and components from used products through reverse logistics activities of remanufacturing and reuse. It considers impacts of environmental protection and green image. Closed-loop supply chains comprising forward and reverse logistics can be combined to achieve more sustainable production and consumption.

There have been numerous studies and research on reverse logistics. The initial approach in the field of reverse logistics is made by Schrady [18]. He analyzed a traditional Economic Order Quantity (EOQ) model for repairable items with the joint coordination of reverse manufacturing with the forward supply chain by assuming that the manufacturing and recovery (repair) rates are instantaneous. His work was generalized by Nahmias and Rivera [12] with finite repair rates. This model is further extended by Koh et al. (2002) for limited repair capacity. Richter [13–15], and Richter and Dobos [16] have investigated the reverse logistics model. In these problems the return rate has been taken as a decision variable. Authors have examined problem with pure or bang-bang policy (total repair or total wastage disposal). Richter [15] concluded in his paper that the bang-bang policy is optimal when compared to mixed (production + remanufacturing) policy, while in later study (El Saadany and Jaber [5] it was observed that mixed strategy is optimal, rather than a pure strategy; either pure remanufacturing or pure production. The model developed by Ishii et al. [6] confirms that life-cycle design seeks to maximize the life-cycle value of a product at the initial stages of design. Savaskan et al. [17] developed a RL model by assuming the returned rate dependent to the Collection investment. In this model they investigated a closed-loop supply chain that includes reverse logistics in times of product recovery of the retailer. Dekker et al. [4] proposed a quantitative model for closed loop supply chain. He analyzed that the amount of returns is highly uncertain and this uncertainty greatly affect the collection and inventory decisions. El Saadany and Jaber [5] developed a model assuming that the collection rate of returned items is dependent on the purchasing price and the acceptance quality level of these returns. Konstantaras and Skouri [8] developed a model of supply chain by considering a general cycle pattern in which a variable number of reproduction lots of equal size are followed by a variable number of manufacturing lots of equal size. They also have studied the case where shortages are allowed in each manufacturing and reproduction cycle. Alamri [1] investigate the optimal returned quantity for a general Reverse Logistics inventory model for the deteriorated items. Green supply chain inventory model with short life cycle product is developed by Chung and Wee [3]. Singh and Saxena [20] investigated a reverse logistics inventory model with time dependent rates under shortages considering the returned rate and holding capacity as a decision variable. Along the same line as Singh and Saxena [20], Singh et al. [19] developed there model for the flexible manufacturing under the stock out situation.

With growing focus on supply chain management firms realize that inventories across the entire supply chain can be more sufficiently managed through great cooperation and better coordination in just in time production system, multiple deliveries is the one way to reduce the inventory level and the total cost. The main goal of this study is to analyse under what conditions (capacity, return rate, remanufacturing rate) a reverse-logistics system should be introduced at a company that uses a JIT production-management system. Numerous researches have been done on the integrated inventory models implementing JIT. Lu [11] proposed a lot splitting model implementing JIT deliveries assuming equal sized multiple shipments. A joint economic lot size model for a single vendor single buyer system has been developed by Benerji [2]. Kim and Ha [9] have developed a lot splitting model and discussed how and when the optimal policy for buyer and supplier can be achieved. Chang and Wee [3] have investigated a green supply chain model implementing JIT delivery.

In this paper we determined the coordination of reverse manufacturing with the forward supply chain in the inventory management. Reverse logistics operations deals with the collection of returns, cleaning of the collected returns and remanufacturing of the reusable collected items, while in the forward supply chain we have taken the single setup and multiple JIT deliveries (SSMD) strategy. The vendor fulfilled buyer's demand with newly produced and remanufactured items of quality standard "as good as those of new products". The produced/remanufactured items are passing through the process of inspection. After inspection the innocent products are delivered to the buyer in $M + N$ deliveries and the rest (deteriorated items or unacceptable for the primary market) are shipped to a secondary market in as-in condition. A general framework of such a system is shown in Fig. 1. In the next Sect. 2, assumptions and notation are provided for model development. In Sect. 3, the study develops an integrated buyer–vendor model with single setup and multiple deliveries. The model considers JIT deliveries, reverse-manufacturing costs and other costs, and derives the optimal replenishment. A numerical example is presented in Sect. 4. Concluding remarks are shown in Sect. 5.

2 Notations and Assumptions

2.1 Notations

C_{if}	Fixed inspection cost
C_{iv}	Variable inspection cost per setup
C_{ins}	The unit variable inspection cost
L_{fs}	The cost of less flexibility
H_B	Unit holding cost for the buyer
T_B	Delivery cycle time for the buyer

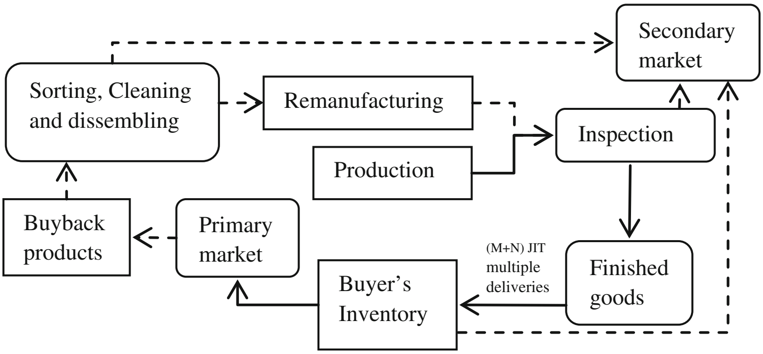

Fig. 1 Material flow in the green supply chain

q	Delivery size per delivery
A	Ordering cost per cycle
P_m	The production rate
D	The demand rate
θ	Deterioration rate
M	Number of deliveries delivered by the producer
U_m	Unit item cost
K_m	Fixed unit production cost
C_m	Variable unit production cost
H_m	Unit holding cost for the produced material
C_s	Selling price for the secondary market
S_s	Selling price for the primary market
P_r	Remanufacturing rate
R	Returned rate
N	The number of deliveries delivered by the remanufacturer
η	Scaling parameter, returned formulation
K_r	Fixed unit reproduction cost
C_r	Variable unit reproduction cost
H_r	Unit holding cost for the remanufactured items
γ	The scaling parameter, returned rate formulation
U_R	Unit returned item cost
H_R	Unit holding cost for the returned items
CI	Collection investment
F_{cl}	Fixed cost including cleaning and disassembly cost during the collecting process
C_{cl}	Variable cost including cleaning and disassembly cost during the collecting process

2.2 Assumptions

- Vendor fulfilled buyer's demand by the newly produced and remanufactured items.
- The buyback products are subject to the cleaning and dissembling process, where the products that confirm to certain quality standard (At a rate of $\left(\frac{1}{\eta}\right)R$) is delivered to remanufacturing unit and the rest $\left\{1 - \left(\frac{1}{\eta}\right)R\right\}$ are shipped for the secondary market in as-in condition.
- Items deteriorate while they are in storage, and production, remanufacturing and demand.
- After the production/remanufacturing products though the inspection process and the deteriorated items are shipped to the secondary market.
- The returned rate R is determined by the collection investment CI. The collection investment represents the monetary amount of effort (e.g., promotion, marketing) that the recycled-material vendor applies to the end-user market to create the necessary incentive to receive targeted returns. We model the return rate similar to the work by Savaskan et al. [17] in which, $R = \left(\sqrt{\frac{CI}{\gamma}}\right)$, where γ is a scaling parameter and $\left(\sqrt{\frac{CI}{\gamma}}\right) < D$
- We shall require that

$$P_r > D, P_m > D, P_r > R,\ D \neq 0,\ R \neq 0$$

3 Mathematical Modelling and Analysis

The items are ordered by buyer in $M + N$ shipments (equal lots of size q). The model assumes that the successive delivering batch arrives at the store as soon as the previous batch has been depleted. For each cycle, the system starts operating at time zero by which the reproduction process starts and the inventory level increases until time T_1, where the stock-level reaches its maximum, and the reproduction process stopped. At the same instant of time production starts and the stock level of remanufactured items decreases continuously due to the demand and deterioration, while production is in process by the time T_2 where it reaches its maximum and the production process stopped. Then the inventory level decrease continuously by the time T_3. The inventory level in returned process decreases until time T_1 where the inventory level becomes zero. After that the inventory level increases until the time $T_1 + T_2 + T_3$ where, the inventory level reaches its maximum. The process is repeated (Fig. 2).

The changes in the inventory levels depicted in Fig. 2 are governed by the following differential equations:

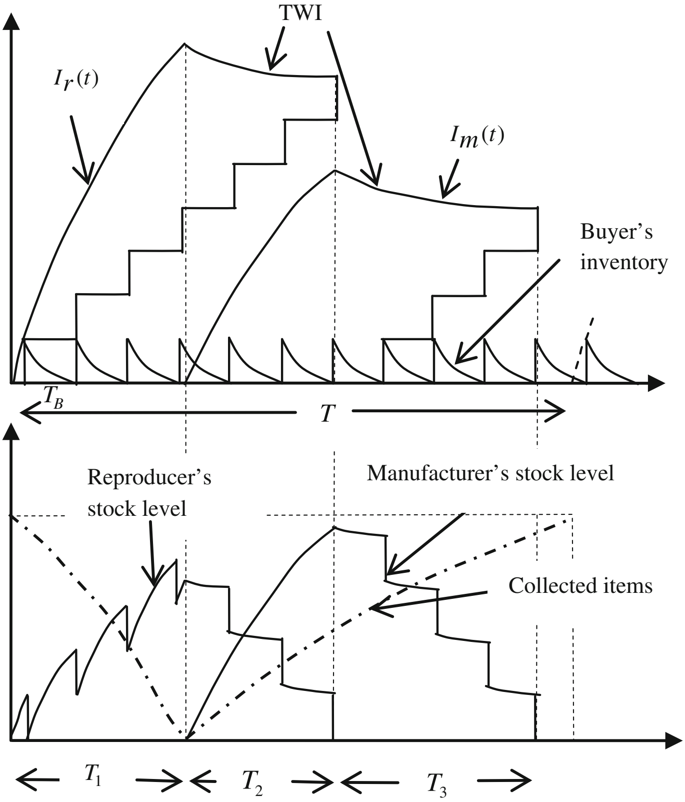

Fig. 2 Inventory variation of an inventory model for reverse logistics systems

$$I'_B(t) = -d - \theta I_B(t), \quad 0 \le t \le T_B \quad I_B(T_B) = 0 \tag{1}$$

$$I'_{r1}(t_{r1}) = P_r - \theta I_{r1}(t_{r1}), \quad 0 \le t_{r1} \le T_1 \quad I_{r1}(0) = 0 \tag{2}$$

$$I'_{r2}(t_{r2}) = -\theta I_{r2}(t_{r2}), \quad 0 \le t_{r2} \le T_2 \quad I_{r2}(T_2) = Nq \tag{3}$$

$$I'_{m1}(t_{m1}) = P_m - \theta I_{m1}(t_{m1}), \quad 0 \le t_{m1} \le T_2 \quad I_{m1}(0) = 0 \tag{4}$$

$$I'_{m2}(t_{m2}) = -\theta I_{m2}(t_{m2}), \quad 0 \le t_{m2} \le T_3 \quad I_{m2}(T_3) = Mq \tag{5}$$

$$I'_R(t_R) = \frac{1}{\eta} R - P_r, \quad 0 \le t_R \le T_1 \quad I_R(T_1) = 0 \tag{6}$$

$$I'_R(t_R) = \frac{1}{\eta} R \quad T_1 \le t_R \le (N+M)T_B \quad I_R(T_1) = 0 \tag{7}$$

The solutions of the above differential equations are

$$I_B(t) = \left\{\frac{d}{\theta}\right\}(e^{\theta(T_B - t)} - 1) \quad 0 \le t \le T_B \tag{8}$$

$$I_{r1}(t_{r1}) = \left\{\tfrac{P_r}{\theta}\right\}(1 - e^{-\theta t_{r1}}) \quad 0 \le t_{r1} \le T_1 \tag{9}$$

$$I_{r2}(t_{r2}) = qNe^{\theta(T_2 - t_{r2})} \quad 0 \le t_{r2} \le T_2 \tag{10}$$

$$I_{m1}(t_{m1}) = \left\{\tfrac{P_m}{\theta}\right\}(1 - e^{-\theta t_{m1}}) \quad 0 \le t_{m1} \le T_2 \tag{11}$$

$$I_{m2}(t_{m2}) = qMe^{\theta(T_3 - t_{m2})} \quad 0 \le t_{m2} \le T_3 \tag{12}$$

$$I_R(t_R) = \left(P_r - \tfrac{1}{\eta}R\right)(T_1 - t_R), \quad 0 \le t_R \le T_1 \tag{13}$$

$$I_R(t_R) = \left\{\tfrac{R}{\eta}\right\}(t_R - T_1), \quad T_1 \le t_R \le (N + M)T_B \tag{14}$$

Respectively

Using the boundary conditions $I_B(0) = q$ so that from Eq. (1), when $\theta \ll; 1$ the delivery size is

$$q = dT_B\left(1 + \frac{\theta T_B}{2}\right) \tag{15}$$

As depicted in Fig. 2 we have

$$T_3 = MT_B \tag{16}$$

and

$$T_1 + T_2 = (N - 1)T_B + \frac{q}{P_r} \tag{17}$$

By which, we get

$$T_1 + T_2 + T_3 = (M + N - 1)T_B + \frac{q}{P_r} \tag{18}$$

Assuming the cycle time T so we have

$$T = (M + N)T_B \tag{19}$$

Using the boundary conditions, from Eqs. (13) and (14) we get

$$\left(P_r - \frac{1}{\eta}R\right)T_1 = \frac{1}{\eta}R((M + N)T_B - T_1)$$

By which the remanufacturing period is

$$T_1 = \frac{R(M + N)T_B}{\eta P_r} \tag{20}$$

From Eq. (17) the production period

$$T_2 = (N-1)T_B + \frac{q}{P_r} - \frac{R(M+N)T_B}{\eta P_r} = \left((N-1) - \frac{R(M+N)}{\eta P_r}\right)T_B + \frac{q}{P_r} \quad (21)$$

Now the per cycle cost components for the given inventory system are as follows.

Sales Revenue from the secondary market

$= c_s\left[(q - dT_B) + \{P_rT_1 + P_mT_2 - q(N+M)\} + \left\{(M+N)\left(1-\frac{1}{\eta}\right)\sqrt{\frac{CI}{\gamma}}\right\}T_B\right]$

Sales Revenue from the primary market

$= S_s d(M+N)T_B$

Buyer's ordering cost and holding cost is as follows

$= A + (M+N)H_B \int_0^{T_B} I_B(u)du$

Production and remanufacturing cost $= K_m + K_r + C_m \int_0^{T_2} P_m du + C_r \int_0^{T_1} P_r du = K_r + K_m + C_rT_1P_r + C_mP_mT_2$

Procurement and acquisition cost

$= U_m \int_0^{T_2} P_m du + U_R \int_0^{(M+N)T_B} R du = U_mP_mT_2 + U_R(M+N)\sqrt{\frac{CI}{\gamma}}T_B$

Inspection cost $= \frac{C_{if}}{M+N} + (M+N)C_{iv} + C_{ins}(P_rT_1 + P_mT_2)$

The Vendor's cost of less flexibility of implementing JIT delivery is $= (M+N)L_{fs}$

As depicted in Fig. 2 the inventory holding cost is

$$\begin{aligned} &= H_m\left[\int_0^{T_2}\left\{\frac{P_m}{\theta}\right\}(1-e^{-\theta u})du + \int_0^{T_3} qMe^{\theta(T_3-u)}du - T_B(q+2q\ldots+(M-1)q)\right] \\ &\quad + H_r\left[\int_0^{T_1}\left\{\frac{P_r}{\theta}\right\}(1-e^{-\theta u})du + \int_0^{T_2} qNe^{\theta(T_2-u)}du - T_B(q+2q\ldots+(N-1)q)\right] \\ &\quad + H_R\left[\int_0^{T_1}\left\{P_r - \frac{1}{\eta}\sqrt{\frac{CI}{\gamma}}\right\}(T_1-u)du + \int_{T_1}^{(M+N)T_B}\frac{1}{\eta}\sqrt{\frac{CI}{\gamma}}(u-T_1)du\right] \\ &\quad + H_B\int_0^{T_B}\left\{\frac{d}{\theta}\right\}(e^{\theta(T_B-t)}-1)du \end{aligned}$$

Cleaning cost $= F_{cl} + C_{cl}\sqrt{\frac{CI}{\gamma}}T_B(M+N)$

Total profit is calculated here,

$$
\begin{aligned}
TP = \frac{1}{T}\Bigg\{ & S_s D(M+N)T_B + c_s\left[(q - DT_B) + \{P_r T_1 + P_m T_2 - q(N+M)\} + (M+N)\left(1-\frac{1}{\eta}\right)\sqrt{\frac{CI}{\gamma}}\right\}T_B\Bigg] \\
& - (M+N)H_B\left[\frac{DT_B^2}{2}\left(1+\frac{\theta T_B}{3}\right)\right] \\
& - A - (U_m + C_m)P_m T_2 - \frac{C_{if}}{M+N} - (M+N)C_{iv} - C_{ins}(P_r T_1 + P_m T_2) - (M+N)L_{fs} \\
& - U_R(M+N)\sqrt{\frac{CI}{\gamma}}T_B - C_r T_1 P_r - F_{cl} - C_{cl}\sqrt{\frac{CI}{\gamma}}T_B(M+N) \\
& - H_m\left[\frac{P_m T_2^2}{2}\left(1-\frac{\theta T_2}{3}\right) + MDT_B T_3\left(1+\frac{\theta T_B}{2}-\frac{\theta T_3}{2}\right) - \frac{1}{2}\left(DT_B^2\left(1+\frac{\theta T_B}{2}\right)M(M-1)\right)\right] \\
& - H_r\left[\frac{P_r T_1^2}{2}\left(1-\frac{\theta T_1}{3}\right) + NDT_B T_3\left(1+\frac{\theta T_B}{2}-\frac{\theta T_2}{2}\right)\right. \\
& \left. - \frac{1}{2}\left(DT_B^2\left(1+\frac{\theta T_B}{2}\right)N(N-1)\right)\right] \\
& - H_R\left[\left(\left(P_r - \frac{1}{\eta}\sqrt{\frac{CI}{\gamma}}\right)\frac{T_1^2}{2} + \frac{1}{\eta}\sqrt{\frac{CI}{\gamma}}\left(\frac{1}{2}(N+M)^2T_B^2 - \frac{T_1^2}{2} - (N+M)T_B T_1 + T_1^2\right)\right] - CI - K_m - K_r\right\}
\end{aligned}
\tag{22}
$$

3.1 Solution Procedure

From Eqs. (15)–(22), the total profit function can be determined in terms of *N, M* and T_B.

Hence the purpose of this study is to derive the optimal number of deliveries and the replenishment cycle time by determining the optimal values of *N, M* and T_B that maximize the total profit. The model has been solved using Algorithm given below.

3.2 Algorithm

Step 1: Taking the first derivative of the total profit function w.r.t. to T_B, equate it equals to zero and then determine the value of T_B

Step 2: Putting the value of T_B in Eq. (25) and then derive the value of N and M by using the following conditions for maximizing the supplier's profit.

$$TP(N,(M-1)|T_B) \le TP(N,M|T_B) \ge TP(N,(M+1)|T_B)$$
$$TP((N-1),M|T_B) \le TP(N,M|T_B) \ge TP((N+1),M|T_B)$$

Step 3: Using the optimum values of *N*, *M* and T_B determine the maximum profit for the system.

Table 1 Optimal results for integrated cost minimization problem

M	N	T_B	q	T_1	T_2	T_3	TC
4	1	1.01094	1016.05	0.361684	0.044735	4.04375	1737.98

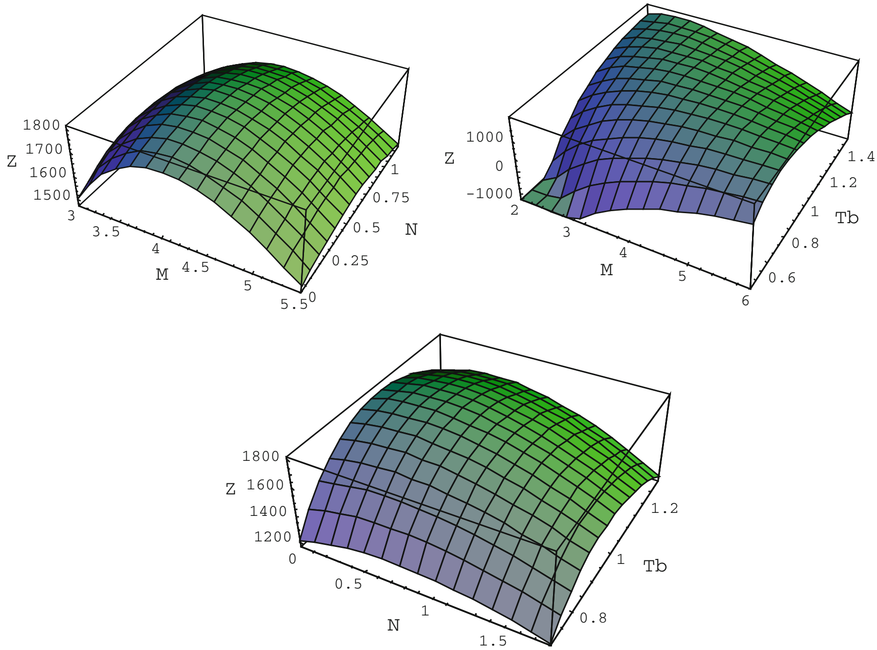

Fig. 3 Convexity of the closed loop supply chain

4 Numerical Analysis and Sensitivity Analysis

Example 1 The above theoretical results are illustrated through the numerical verification, to illustrate the proposed model we have considered the following input parameters in appropriate units

$P_r = 2500,\ P_m = 1200,\ d = 1000,\ \theta = 0.01,\ \eta = 5,\ CI = 8000,\ \gamma = 0.01,$ $A = 500,\ H_B = 1,\ H_r = 1,\ H_R = 0.8,\ H_m = 1,\ K_m = 1000,\ K_R = 1000,\ C_m = 6,$ $C_r = 3,\ U_R = 3,\ U_m = 4,\ C_S = 6,\ S_S = 12,\ C_{if} = 3000,\ C_{iv} = 500,\ C_{ins} = 0.5,$ $L_{fs} = 100,\ C_{cl} = 0.2,\ F_{cl} = 1500.$

Mathematica 8.0 is used to derive the optimal solution and results are presented in Table 1.

The convexity of the reverse logistics inventory model is shown in Fig. 3. The three dimensional graph shows that the integrated expected total profit is concave, and that there exists a unique solution maximizing the integrated expected total profit.

Table 2 Sensitivity analysis for the production, remanufacturing and demand rate parameters F_{cl}, C_{iv}, A, η, γ, P_m, P_r and d

		M	N	T_B	q	T_1	T_2	T_3	TP
γ	−10 %	4	1	1.00837	1013.45	0.38028	0.0251014	4.03348	1844.32
	0 %	4	1	1.01094	1016.05	0.361684	0.044735	4.04375	1737.98
	+10 %	4	1	1.01315	1018.28	0.345606	0.0617059	4.05259	1646.42
η	−10 %	4	1	1.00566	1010.72	0.399773	0.00451352	4.02264	1678.06
	0 %	4	1	1.01094	1016.05	0.361684	0.044735	4.04375	1737.98
	+10 %	4	1	1.01525	1020.41	0.330207	0.0779554	4.06101	1786.73
P_m	−10 %	4	1	1.01098	1016.09	0.361698	0.0447368	4.04391	1742.78
	0 %	4	1	1.01094	1016.05	0.361684	0.044735	4.04375	1737.98
	+10 %	4	1	1.0109	1016.01	0.36167	0.0447332	4.0436	1733.18
P_r	−10 %	4	1	1.01061	1015.72	0.401741	0.0496887	4.04244	1730.9
	0 %	4	1	1.01094	1016.05	0.361684	0.044735	4.04375	1737.98
	+10 %	4	1	1.01121	1016.32	0.328891	0.0406795	4.04483	1743.76
d	−10 %	4	1	1.05883	957.989	0.378817	0.00437826	4.23531	1459.25
	0 %	4	1	1.01094	1016.05	0.361684	0.044735	4.04375	1737.98
	+10 %	4	1	0.968789	1070.83	0.346605	0.0817275	3.87516	2027.14
A	−10 %	4	1	1.00936	1014.45	0.361118	0.0446618	4.03743	1747.88
	0 %	4	1	1.01094	1016.05	0.361684	0.044735	4.04375	1737.98
	+10 %	4	1	1.01252	1017.64	0.362249	0.0448081	4.05007	1728.09
C_{iv}	−10 %	4	1	1.003	1008.03	0.358845	0.044368	4.01201	1787.63
	0 %	4	1	1.01094	1016.05	0.361684	0.044735	4.04375	1737.98
	+10 %	4	1	1.01881	1024.00	0.364499	0.0450992	4.07523	1688.71
F_{cl}	−10 %	4	1	1.00619	1011.25	0.359984	0.0445151	4.02474	1767.72
	0 %	4	1	1.01094	1016.05	0.361684	0.044735	4.04375	1737.98
	+10 %	4	1	1.01567	1020.83	0.363376	0.0449539	4.06267	1708.37

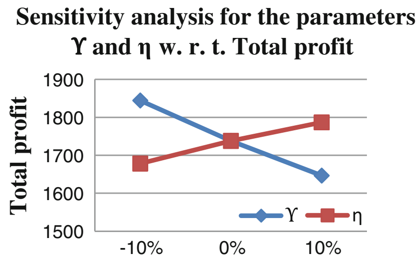

Fig. 4 Effect of returned rate on total profit

Example 2 We now study the effects of changes in the values of the system parameters F_{cl}, C_{iv}, A, η, γ, P_m, P_r and d on the optimal total profit and number of reorder. The sensitivity analysis is performed by changing each of the parameters by −10, 0 and 10 %, taking one parameter at a time and keeping the remaining parameters the same as in Example 1. The sensitivity analyses of the different parameters are shown in Table 2. The graphical representation of the sensitivity of decision variables is provided in Figs. 4, 5 and 6.

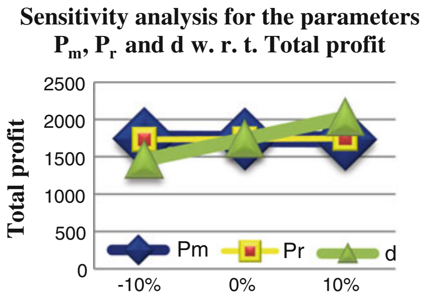

Fig. 5 Effect of production, remanufacturing and demand on total profit

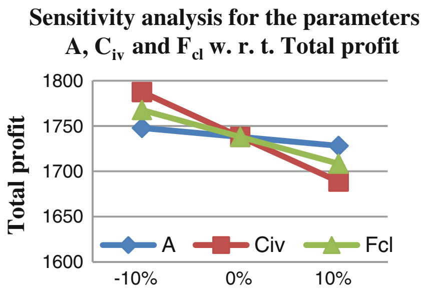

Fig. 6 Effect of ordering, inspection and cleaning cost on total profit

4.1 Observations

1) Table 2 revels that the total profit is positive sensitive to the changes in parameter η while negative sensitive to the changes in parameter γ hence it seems that to procure the used products from the user is profitable but resell them in the secondary market in as-is condition is better than the remanufacturing.
2) From the table it is observed that the total profit is slightly negative sensitive to the changes in parameter P_m while slightly positive sensitive to the changes in parameter P_r. Hence it can be said that remanufacturing is more profitable than the production.
3) Table 2 reveals that the total profit is moderately positive sensitive to the changes in demand parameter. This is a logical tendency since it allows the vendor and buyer to get more cost savings from accumulated revenue.
4) From the table it is observed that the total profit is moderately positive sensitive to the changes in parameters F_{cl}, C_{iv} and A which is obvious. But if we compare the behaviour of these three parameters it is noted that the cleaning cost is more sensitive than the ordering cost while less sensitive than the inspection cost.

5 Conclusion

In the presented paper we have discussed the effect of JIT on a green supply chain inventory model. Here we have determined the model for the deteriorating products where the deteriorated products are delivered to the secondary market. In this article we derived a profit function for the mathematical model developed here and hence determine the optimal results with the help of a numerical example. The results shows that the reselling the used products in the secondary market is profitable than the remanufacturing. In the further study the model can be developed for the remanufactured items whose quality standard is not as good as those of new products.

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