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SUSTAINABLE PRODUCTION POLICIES UNDER THE EFFECT OF VOLUME AGILITY, PRESERVATION TECHNOLOGY, AND PRICE-RELIANT DEMAND

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Abstract: Any supply chain supposes production and pricing decisions. The most influential factor that affects a sales decision is the price of a product, which in turn, affects the configuration of the demand. Further, holding the produced goods means also the occurrence of deterioration as a common phenomenon, which may lead to excessive loss if left untreated. Thus, an investment in preservation process helps in controlling deterioration efficiently. Moreover, incorporation of the environmental factor presents the need of the hour in the current situation of environmental imbalance. To address the above issues, we consider volume agility to avoid any excessive storage and backlogging costs, carbon-emissions and energy-usage to address the performance of our model regarding the environment, and investment in preservation process to control the loss due to deterioration. Also, the demand of the product is taken as price-reliant. The investment in

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preservation, production rate, and price of the product are taken as the decision variables so as to maximize the total inventory turnover. Validity and robustness of the model is analyzed through numerical and sensitivity analysis. A wide-ranging applicability of the developed study is also provided.

Keywords: Inventory, Production, Volume agility, Deterioration, Preservation technology, Energy usage, Price-reliant demand, Carbon-emissions.

MSC: 90B05, 90B30.

1. INTRODUCTION

In manufacturing systems, the constant production rate has been explicitly assumed by numerous researchers. Such an assumption holds only if the demand of a product is known with certainty. However, with constant changes in the markets and recent trends, the demand of a product fluctuates in the long run, which may lead to shortages or high storage costs, depending upon the rise or fall. Thus, volume agility is an effective tool to deal with this situation efficiently. [46] put forth a pioneer research by introducing a theory on agility in the manufacturing process. Further, the impact of flexible production rate on various production models has been studied by [33], [31], and [32], etc. [43] investigated a scenario for a decaying product under the assumption of flexible production rate. Later, [42] explored the optimum policy for a decaying product with volume agility where the demand is assumed to be dependent on inventory level. Then, [41] studied a manufacturing system with faulty products along with volume agility. [50] examined the effect of inflation in a defective manufacturing scenario and flexible production. [51] inspected an ordering model with volume agility, variable demand, and inflation. [14] also formulated a model with flexible production rate. [13] studied an ordering system with multiple items and greening under the assumption of flexible production rate. [44] modeled a two-warehouse vendor-supplier framework with volume agility.

The growing concern towards the environment enabled researchers to implement the realistic features such as carbon-emissions and energy usage in their modeling, caused largely by customers' awareness and the sustainability aspect of business. Various researchers incorporated energy usage viz. [6], [5], [35], etc. [36] presented a supply-chain model with carbon-footprints, energy consumption, and imperfect process. In the same year, [34] developed a production model with learning in the manufacturing process and energy efficiency.

Further, the environment experts are signifying the importance of green strategies as they are beneficial in both ways, economically and environmentally. [15], [45], [49] studied carbon footprints in their respective inventory modeling. Lately, [20] constructed a sustainable and integrated supply chain model with an investment in setup cost along with harmful carbon emissions. Recently, [21] put forth a sustainable supply chain scenario with features like defect management, carbon-emissions, and more. In the same year, [11] proposed a three tier supply chain model with deteriorating items and carbon-emissions, and [4] studied the reduced impact of carbon-emissions in the supply chain with vendor managed inventory of deteriorating items.

The inventory reduction caused by deterioration cannot be overlooked in an inventory system. The presence of deterioration affects the revenue and thereby decreases the total profit of the system. The foremost research in this area was given in [22]. Later, [12], [55], [7], [23], [25], etc. analyzed the topic in detail. Some models with constant and Weibull deterioration rate were also developed by [37], [47], etc. If the products are prone to deterioration, they require a special care to be handled and the due loss to be minimized. In this regard, preservation technology is an efficient strategy to minimize the loss occurred due to deterioration. [27], [17], [18], [51], and [58] to mention a few. Freshly, in [30], [24], and [19], this field has been explored under various assumptions. Lately, [40], studied the preservation technology model for deteriorating items with trade-credit. From the above-mentioned studies, it can be observed that the effect of preservation technology along with volume agility on optimal policies has not been studied yet.

The demand in its nature is always price sensitive. So, determination of a selling price is the most crucial decision of any business. Various researchers studied different natures of demand. Its price-sensitive nature was explored by [1], [2], [39], [3], [8], [16], [10], and [9] under various other practical settings like deterioration, partial backordering, credit period, lead time considerations, etc. The demand depending upon both the price and stock was explored by [38]. However, the demand depending upon the price and time was studied by [56], [54], etc. Later, [57] developed a dynamic pricing model for seasonal goods under spot and forward purchase demand pattern. [53] investigated a supply chain scenario under stochastic demand environment. Lately, [29] developed an inventory scenario with mark-up price reliant demand for products of imperfect quality under credit-policies, shortages, and deterioration.

Our model has the following research questions and highlights:

- How the preservation strategies assist in controlling the deterioration rate?
- The basic nature of demand is considered as price-sensitive.
- The rate of production is assumed to be variable, thus, the concept of volume agility is implemented.
- What is energy usage? How is it implemented in the production scenario?
- The environmental aspect is considered through the incorporation of carbon-emission while production and storage of goods.
- What will be the optimum production rate, investment in preservation technology, and selling price under the proposed production policy?
- What will be the behavior of the model under changing parameters?

The present framework fulfills the current literature gap by proposing a production inventory model for decaying items. The product's demand is supposed to be price-reliant. Further, the production rate is not constant, instead, the concept of volume agility is incorporated. An investment in preservation strategy is considered to curb the loss due to deterioration. The environmental aspect of the business is also showcased through the consideration of carbon-emissions and energy consumptions costs.

2. NOTATIONS AND ASSUMPTIONS

2.1. Notations

t_1 = time where the production stops (weeks)
T = time where the inventory cycle ends (weeks)
h_1 = storage cost of the item ($/unit/unit time)
d_1 = deterioration cost of the item ($/unit/unit time)
K = setup cost per order
ξ = material cost per unit (fixed)
ω = labour cost
ϖ = tool/die cost
$\delta(\psi)$ = rate of deterioration with preservation technology (units/ unit time), ($\delta(\psi) = y_0 e^{-u\psi}$)
y_0 = rate of deterioration when investment in preservation strategy is zero (units/ unit time)
u = the sensitive parameter of preservation technology investment to the deterioration rate ($0 < u < 1$)
$\lambda(S)$ = rate of demand as a function of selling price ($\lambda(S) = \alpha - \beta S$) (units/unit time)
α = demand scale
β = price sensitive parameter
γ = idle power for the manufacturing process in the start position (kW)
j = variable component of the power, a constant (kWh/unit)
b_1 = energy cost
e_p = carbon emission cost in production
e_h = carbon emission cost in holding

Decision variable

ψ = cost of preservation technology investment ($/unit/unit time)
P = production rate
S = selling price ($/unit)

2.2. Assumptions

1. The model considers only a single item.
2. The lead time is zero and backlogging is not allowed.
3. The rate of demand $\lambda(S)$ is a function of sales price S:

$$\lambda(S) = \alpha - \beta S$$

where α is the demand scale, and β is price sensitive parameter.

4. The production rate P is flexible, where P is greater than demand rate.
5. The unit production cost $\chi(P) = \left(\xi + \frac{\omega}{P} + \varpi P\right)$ where ξ, ω, ϖ are all positive constants. The production cost/unit $\left(\frac{\omega}{P}\right)$ tends to decrease as rate of production (P) increases. Further,the last term (ϖP) related to the tool/die costs is proportionate with respect to production rate.
6. The proportion of reduced deterioration rate after using investment in preservation strategy is $\delta(\psi) = y_0 e^{-u\psi}$, and this function satisfies the following conditions $\delta'(\psi) > 0$, $\delta''(\psi) < 0$ and $\delta(0) = y_0$.

3. MATHEMATICAL MODEL

The proposed scenario is depicted in Figure 1. The cycle begins at time zero with no inventory and rises till t_1 at rate P and concurrently reduces due to demand and deterioration. During (t_1, T), the inventory diminishes only due to demand rate and deterioration. The deterioration rate is being skillfully taken care of by an investment in preservation policy. Finally, the inventory exhausts at time T.

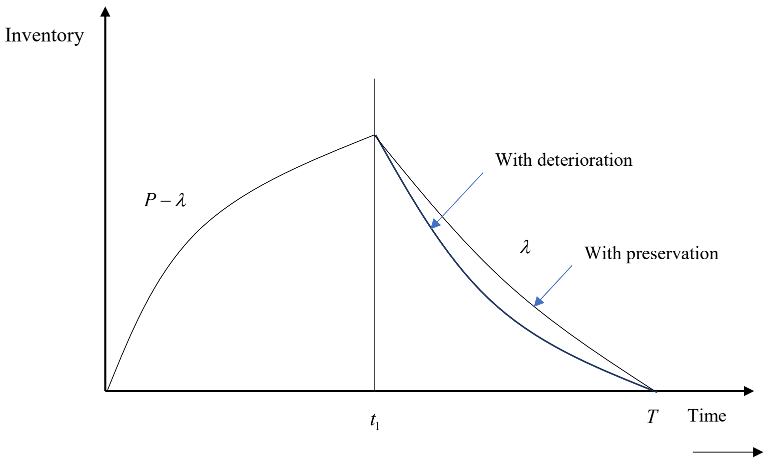

Figure 1: Inventory representation

During the time interval $(0, t_1)$

$$\frac{dI_1(t)}{dt} + \delta(\psi)I_1(t) = P - \lambda(S), \quad 0 \le t \le T_1 \tag{1}$$

Using $I_1(0) = 0$, the solution of Eq. (1) is

$$I_1(t) = \frac{(P - \lambda(S))}{\delta(\psi)}(1 - e^{\delta(\psi)t}) \tag{2}$$

During (t_1, T), the inventory equation is depicted as:

$$\frac{dI_2(t)}{dt} + \delta(\psi)I_2(t) = -\lambda(S), \quad t_1 \le t \le T \tag{3}$$

Using $I_2(T) = 0$, the solution of Eq. (3)

$$I_2(t) = \frac{\lambda(S)}{\delta(\psi)}(e^{\delta(\psi)(T-t_1)} - 1) \tag{4}$$

Now put $t = t_1$ in Eq. (2) and (4) we have

$$t_1 = \frac{1}{\delta(\psi)} \ln\left[1 + \frac{\lambda(S)}{P}\left(e^{\delta(\psi)T} - 1\right)\right] \tag{5}$$

The different components are:

- Set-up cost

$$SC = K \tag{6}$$

- Storage cost HC

$$\begin{aligned} HC &= h_1 \left[\int_0^{t_1} I_1(t)\,dt + \int_{t_1}^{T} I_2(t)\,dt\right] \\ &= \frac{h_1}{\delta(\psi)^2}\{[(P - \lambda(S))(t_1\delta(\psi) + e^{-\delta(\psi)t_1} - 1)] \\ &\qquad + [\lambda(S)(e^{\delta(\psi)(T-t_1)} - 1 - (T - t_1)\delta(\psi))]\} \end{aligned} \tag{7}$$

- Deterioration cost DC

$$\begin{aligned} DC &= d_1\delta(\psi) \left[\int_0^{t_1} I_1(t)\,dt + \int_{t_1}^{T} I_2(t)\,dt\right] \\ &= \frac{d_1}{\delta(\psi)}\{[(P - \lambda(S))(t_1\delta(\psi) + e^{-\delta(\psi)t_1} - 1)] \\ &\qquad + [\lambda(S)(e^{\delta(\psi)(T-t_1)} - 1 - (T - t_1)\delta(\psi))]\} \end{aligned} \tag{8}$$

- Preservation cost

$$P_C = \psi.T \tag{9}$$

- Production cost PC

$$\begin{aligned} PC &= \left(\xi + \frac{\omega}{P} + \varpi P\right)\int_0^{t_1} P dt \\ &= Pt_1\left(\xi + \frac{\omega}{P} + \varpi P\right) \end{aligned} \tag{10}$$

In order to obtain the energy costs, we define

$$\eta = \gamma + j.P \tag{11}$$

where j is fixed (kWh/unit) derived from the behavior of the manufacturing system (see [26]).

From (11), the specific energy usage /unit of treated material is (see [36]):

$$SEC = \frac{(\gamma + j.P)t_P}{P.t_P} \tag{12}$$

- Energy cost

$$EC = b_1(SEC.\lambda(S)) \tag{13}$$

- Carbon emission cost in production

$$CP = e_p.P.t_1 \tag{14}$$

- Carbon emission cost in holding

$$\begin{aligned} CH &= e_h\left[\int_0^{t_1} I_1(t)\,dt + \int_{t_1}^{T} I_2(t)\,dt\right] \\ &= \frac{e_h}{\delta(\psi)^2}\{[(P-\lambda(S))(t_1\delta(\psi) + e^{-\delta(\psi)t_1} - 1)] \\ &\qquad + [\lambda(S)(e^{\delta(\psi)(T-t_1)} - 1 - (T-t_1)\delta(\psi))]\} \end{aligned} \tag{15}$$

- Total Revenue

$$TR = \lambda(S) \bullet T \bullet S \tag{16}$$

- Total profit

$$\begin{aligned} TP &= [TR - (SC + HC + DC + P_C + PC + EC + CP + CH)] \\ &= \frac{\lambda(S)TS}{T} - \left(\frac{K}{T} + \frac{(h_1+e_h)}{T\delta(\psi)^2}\{[(P-\lambda(S))(t_1\delta(\psi) + e^{-\delta(\psi)t_1} - 1)]\right. \\ &\quad + \lambda(S)(e^{\delta(\psi)(T-t_1)} - 1 - (T-t_1)\delta(\psi))\} \\ &\quad + \frac{d_1}{T\delta(\psi)}\{[(P-\lambda(S))(t_1\delta(\psi) + e^{-\delta(\psi)t_1} - 1)] \\ &\quad + \lambda(S)(e^{\delta(\psi)(T-t_1)} - 1 - (T-t_1)\delta(\psi))\} \\ &\quad \left. + \psi + \frac{Pt_1}{T}\left(\xi + \frac{\omega}{P} + \varpi P\right) + \frac{b_1(SEC.\lambda(S))}{T} + \frac{e_p.P.t_1}{T}\right) \end{aligned} \tag{17}$$

$$
\begin{aligned}
&= \lambda(S)S - \frac{(h_1+e_h)}{T}\left[(P-\lambda(S))\left(\frac{t_1^2}{2}\right) + \frac{\lambda(S)\left(T-t_1\right)^2}{2}\right] \\
&\quad - \frac{d_1}{T}\left[\frac{(P-\lambda(S))\,t_1^2\delta(\psi)}{2} + \frac{\lambda(S)\delta(\psi)\left(T-t_1\right)^2}{2}\right] \\
&\quad - \frac{K}{T} - \alpha - \frac{Pt_1}{T}\left(\xi + \frac{\omega}{P} + \varpi P\right) \\
&\quad + b_1\frac{(\gamma + j.P)t_P}{P.t_P.T}.\lambda(S) + \frac{e_p.P.t_1}{T}
\end{aligned} \tag{18}
$$

Solution procedure

Now, to establish the optimality of equation (13), the necessary condition satisfied these equations:

$$\frac{\partial TP(S,\psi,P)}{\partial S} = 0 \tag{19}$$

$$\frac{\partial TP(S,\psi,P)}{\partial P} = 0 \tag{20}$$

$$\frac{\partial TP(S,\psi,P)}{\partial \psi} = 0 \tag{21}$$

The sufficient conditions for maximize the total profit are $H_1 < 0$, $H_2 > 0$, $H_3 < 0$, the hessian matrix H is estimated as:

$$H = \begin{bmatrix} \frac{\partial^2 TP}{\partial \psi^2} & \frac{\partial^2 TP}{\partial \psi \partial S} & \frac{\partial^2 TP}{\partial \psi \partial P} \\ \frac{\partial^2 TP}{\partial S \partial \psi} & \frac{\partial^2 TP}{\partial S^2} & \frac{\partial^2 TP}{\partial S \partial P} \\ \frac{\partial^2 TP}{\partial P \partial \psi} & \frac{\partial^2 TP}{\partial P \partial S} & \frac{\partial^2 TP}{\partial P^2} \end{bmatrix}$$

and

$$H_1 = \frac{\partial^2 TP}{\partial \psi^2},$$

$$H_2 = \begin{vmatrix} \frac{\partial^2 TP}{\partial \psi^2} & \frac{\partial^2 TP}{\partial \psi \partial S} \\ \frac{\partial^2 TP}{\partial S \partial \psi} & \frac{\partial^2 TP}{\partial S^2} \end{vmatrix}$$

$$H_3 = \det H = \begin{vmatrix} \dfrac{\partial^2 TP}{\partial \psi^2} & \dfrac{\partial^2 TP}{\partial \psi \partial S} & \dfrac{\partial^2 TP}{\partial \psi \partial P} \\ \dfrac{\partial^2 TP}{\partial S \partial \psi} & \dfrac{\partial^2 TP}{\partial S^2} & \dfrac{\partial^2 TP}{\partial S \partial P} \\ \dfrac{\partial^2 TP}{\partial P \partial \psi} & \dfrac{\partial^2 TP}{\partial P \partial S} & \dfrac{\partial^2 TP}{\partial P^2} \end{vmatrix}$$

where H_1, H_2, and H_3 are the minors of the Hessian matrix H.

Due to the extremely non-linear nature of the profit function, the sufficient condition can not be proven mathematically, thereby graphical method is employed to establish concavity and is represented in Figures 2, 3, and 4 with the help of Mathematica.

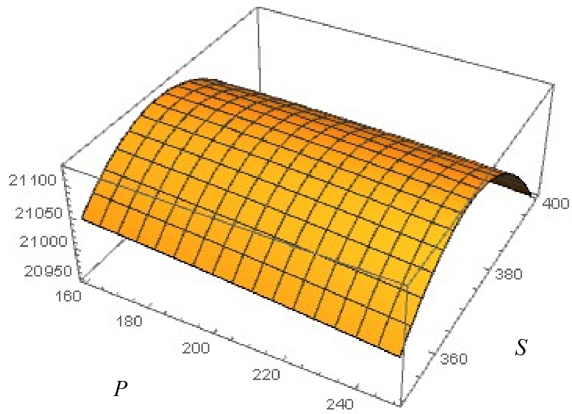

Figure 2: Concavity for profit vs. P and S

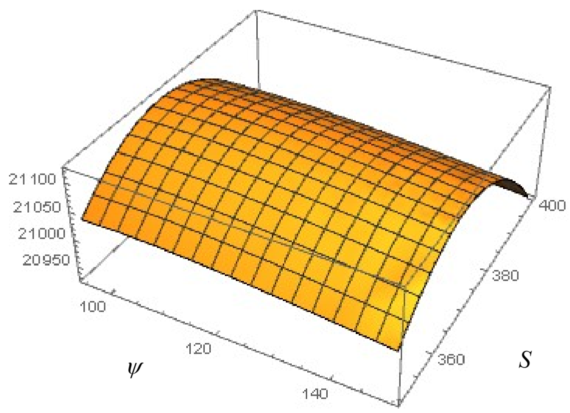

Figure 3: Concavity for profit vs. ψ and S

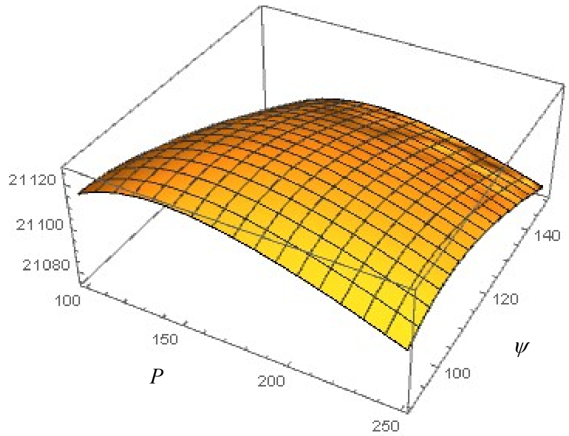

Figure 4: Concavity for profit vs. ψ and P

Numerical Example

The developed model is demonstrated using a numerical example. The following parameter values are taken in appropriate units for the numerical illustration: $u = 0.05$, $y_0 = 0.05$, $h_1 = 1.5$, $\xi = 25$, $\omega = 1300$, $\varpi = 0.008$, $K = 600$, $\alpha = 140$, $\beta = 0.2$, $d = 250$, $T = 11$, $\gamma = 100$, $j = 10$, $e_p = 3$, $e_h = 1.5$, $b_1 = 0.15$.

The following optimal results are obtained:

Total profit = 21096.05, Production rate = 191.56, Selling price = 371.36, investment in preservation technology = 103, Production time = 3.78

Sensitivity Analysis

		t_1 (production time)	ψ (investment in preservation)	P (production rate)	S (selling price)	Total profit
	120	2.5817	102.77	236.71	322.56	15036.15
	130	3.0974	103.23	215.43	347.02	17938.12
α	140	3.7784	103.00	191.56	371.36	21096.05
(demand scale)	150	4.7783	101.47	163.41	395.44	24511.76
	160	6.7976	94.97	123.51	418.73	28189.52
	0.16	3.9191	102.86	187.14	458.72	27202.92
	0.18	3.8476	102.93	189.37	410.18	23809.18
β	0.20	3.7784	103.00	191.56	371.36	21096.05
(price sensitive)	0.22	3.7106	103.06	193.74	339.60	18877.93
	0.24	3.6447	103.11	195.91	313.15	17031.08

Table 1:

- The increase in the demand scale parameter (α) increases the demand (see Table 1). Thus, higher number of units are required to be produced in order to meet the demand, which eventually increases the production time along with the decrease in the production rate. Also, due to increase in demand, the movement of goods will be fast, thus, the deterioration will be reduced, hence, the investment in preservation process is also reduced. High demand implies higher sales, thus profit is increasing.To make the best out of this condition, the price of a product can be increased to fetch higher profits.

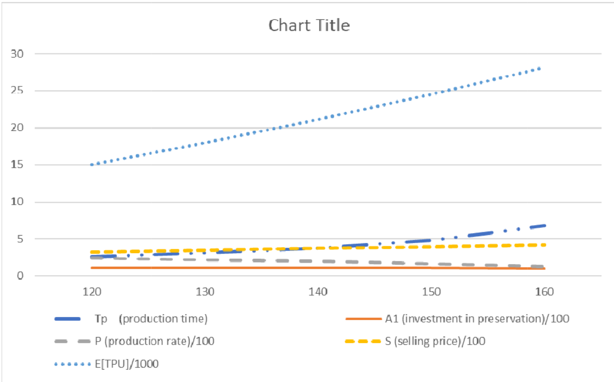

Figure 5: Sensitivity with respect to α

- An upsurge in price-sensitive parameter (β) of demand reduces the total profit due to the negative aspect of β on demand (see Table 1). Further, due to decreased sales, the accumulated inventory will deteriorate, thus, investment in preservation will be increased. The decision makers may give some lucrative offers to the customers in order to boost sales.

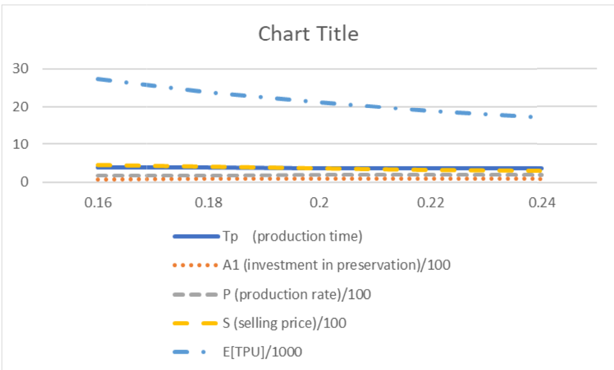

Figure 6: Sensitivity with respect to β

		t_1	ψ	P	S	Total profit
u (sensitive parameter of preservation)	0.01	-	-	-	-	-
	0.03	3.9273	153.97	184.45	371.30	21031.21
	0.05	3.7784	103.00	191.56	371.36	21096.05
	0.07	3.7216	78.49	194.41	371.38	21126.41
	0.09	3.6903	63.89	196.02	371.39	21144.24

Table 2:

- A rise in the sensitive parameter of preservation (u) increases the effectiveness of the preservation technology even if lesser is invested in it, thus, investment is decreasing (see Table 2). The decision-makers may increase the production rate so as to take benefit of this situation. In accordance with this, the total profit increases.

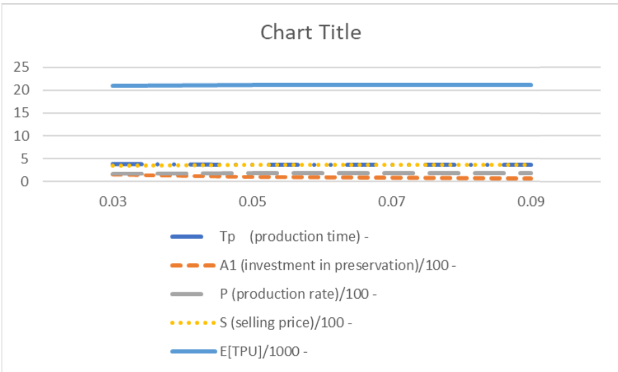

Figure 7: Sensitivity with respect to u

		t_1	ψ	P	S	Total profit
e_p (emission in production)	0.8	3.8135	102.82	190.45	370.22	21241.06
	1	3.8108	102.83	190.52	370.63	21227.85
	3	3.7784	103.00	191.56	371.36	21096.05
	5	3.7465	103.17	191.58	372.39	20964.66
	7	3.7152	103.33	193.59	373.42	20833.69
e_h (emission in holding)	1.1	3.0894	104.81	234.26	371.38	21196.06
	1.3	3.3805	104.07	214.05	371.43	21144.94
	1.5	3.7784	103.00	191.56	371.36	21096.05
	1.7	4.3765	101.28	165.52	371.07	21050.34
	1.9	5.4807	97.65	132.49	370.28	21009.85

Table 3:

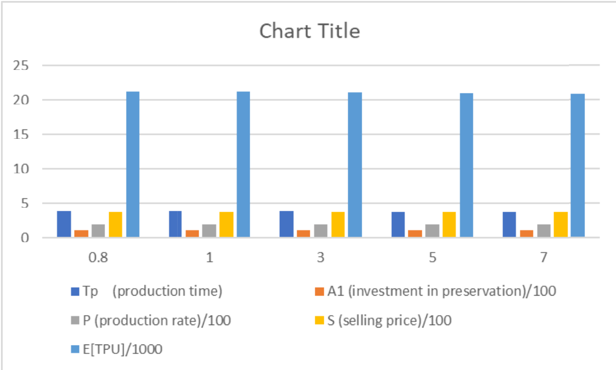

Figure 8: Sensitivity with respect to e_p

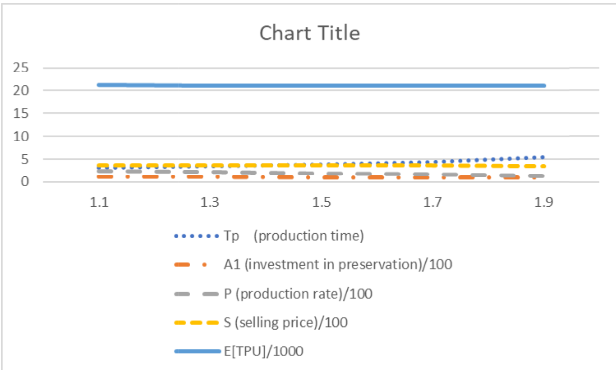

Figure 9: Sensitivity with respect to e_h

- The carbon-emission costs increase when production and storage of goods result in decreasing the total profits (see Table 3). Further, for such a situation it is necessary to monitor the demand so as to produce only the requisite quantity and avoid emissions during production and holding of goods.

		t_1	ψ	P	S	Total profit
b_1 (cost of energy)	0.05	4.4179	101.15	164.25	370.50	21121.77
	0.10	4.0561	102.23	178.65	370.97	21108.38
	0.15	3.7784	103.00	191.56	371.36	21096.05
	0.20	3.5553	103.61	203.37	371.69	21084.56
	0.25	3.3700	104.10	214.37	371.97	21073.74

Table 4:

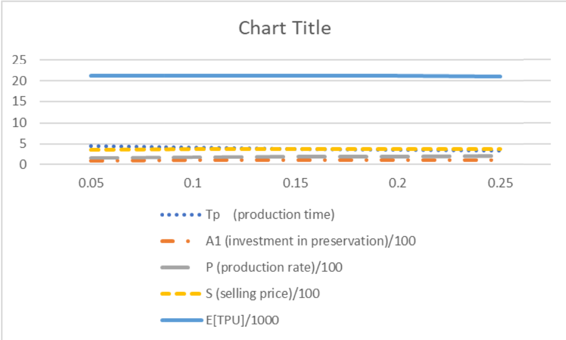

Figure 10: Sensitivity with respect to b_1

- A rapid manufacturing boost the energy consumption and related carbon-footprints. Further, when the energy cost increases, the total profit of the system decreases (see Table 4). For such a case it is suggested that a bigger lot size with a lower speed can assist in reducing the energy usage.

		t_1	ψ	P	S	Total profit
ω (labour cost)	1200	4.7269	100.17	153.56	370.41	21134.2
	1250	4.1697	101.88	173.79	370.94	21114.07
	1300	3.7784	103.00	191.56	371.36	21096.05
	1350	3.4820	103.81	207.65	371.69	21079.58
	1400	3.2469	104.44	222.49	371.97	21064.3
ϖ (tool/die cost)	0.004	2.6601	105.84	271.82	371.82	21155.2
	0.006	3.2648	104.36	221.59	371.51	21123.09
	0.008	3.7784	103.00	191.56	371.36	21096.05
	0.010	4.2346	101.71	170.99	371.22	21072.27
	0.012	4.6518	100.46	155.71	371.09	21050.81

Table 5:

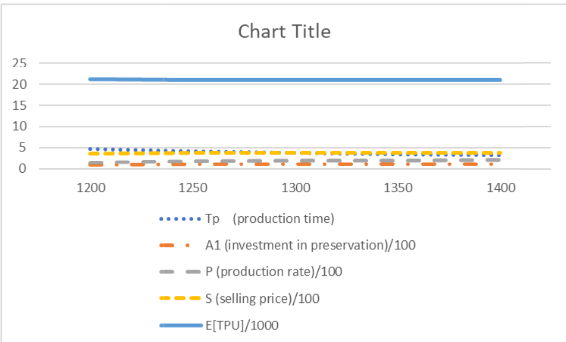

Figure 11: Sensitivity with respect to ω

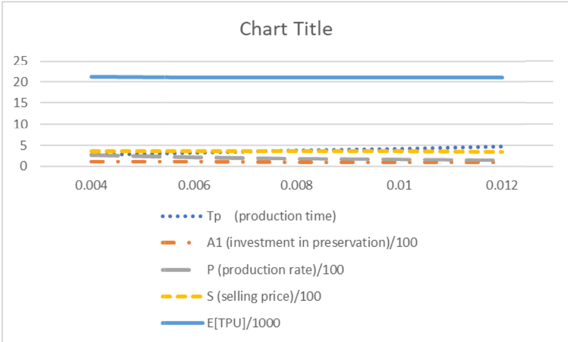

Figure 12: Sensitivity with respect to ϖ

- The costs linked with production system affect the overall system costs significantly. When the labour cost increases, the production time duration decreases, and the rate of production is increased. The total profit decreases slightly (see Table 5).
- When the tool/die cost increases, production time increases, however, the rate of production decreases. The total turnover decreases considerably (see Table 5).

4. CONCLUSION

Environmental issues can be addressed in a sustainable way by adopting green techniques in the manufacturing world. It is important to implement the environmental factors such as carbon-emissions during production & storage of goods, energy usage while production, etc., so as to give a model that fits the current need of economic and environmental crisis. Hence, we developed a production model with items of deteriorating quality and demand being price-sensitive with volume agility, and considered investment in preservation technology to deal with deterioration. The incorporation of volume agility enables manufacturers to manage fluctuating demand efficiently. Also, we took the environmental aspects into consideration by implementing the carbon-emissions and energy usage during the production process. Numerical and sensitivity analysis are performed for structuring the model features and to impart useful managerial insights. A valuable contribution of the developed model could be made by executing non-instantaneous deterioration. Further, the presence of imperfect quality items and disruption can also be accounted in the manufacturing process.

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