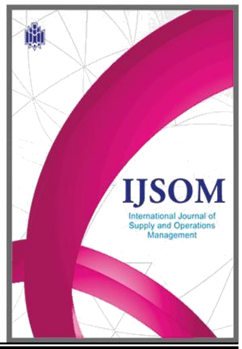
International Journal of Supply and Operations Management

# IJSOM

2023, Volume 10, Issue 2, pp. 136-150
ISSN-Print: 2383-1359
ISSN-Online: 2383-2525
www.ijsom.com




## COVID -19 Impact on a Sustainable Production Model with Volume Agility and Advertisement Dependent Demand

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## Abstract

The novel coronavirus has a significant impact on the whole world, especially the manufacturing sector. In this pandemic, the demand of personal protective equipment (PPE) viz., masks, face shields, gloves, hand sanitizer, etc., has increased rapidly, which has put an additional pressure on the manufacturers to increase their production to meet the escalating demand. Thus, the agile nature of demand can be addressed by incorporating volume agility in the production process. Accordingly, there is an urgent need for the manufacturers to promote their products and also to keep the public aware about the importance of various preventive measures. However, as the pandemic continues, the excess production of PPE leads to a considerable amount of carbon emissions and waste in the environment. Motivated by this, the present study develops a sustainable production model with volume agility and advertisement sensitive demand. Sustainability is addressed by incorporating carbon emission costs during the production and inventory holding. The objective is to maximize the total profit by conjointly optimizing the cycle length, advertising cost, and production rate. A numerical example is included to validate the model. Further, the sensitivity analysis unfolds valuable managerial insights for decision-makers to better management in this pandemic.

**Keywords:** Inventory; PPE; COVID-19; Volume agility; advertisement dependent demand; Carbon emissions.

### 1. Introduction

COVID-19 has posed unprecedented challenges for nations worldwide. The global impact of the COVID-19 pandemic has resulted in the economic and health crisis all over the world. To prevent the spread of the virus, governments have introduced various measures such as travel restrictions, social distancing, closing educational institutes, public places, and nearly all businesses. The sudden outbreak induces insufficient supply in terms of raw materials, production rate, and disruption in the supply chain to fulfill the surging demand of the PPE (such as masks, face shields, gloves, hand sanitizer, etc.).

In a time of such extreme uncertainty, adequate production and distribution of PPE has become one of the main challenges to overcome. Governments and health care officials have introduced protective measures (e.g. masks, face shields, gloves, hand sanitizer, etc.) to suppress the outbreak. In the case of a sudden surge in demand, traditional manufacturers are unable to prepare the necessary quantity of personal protective products, therefore government encourages non-traditional manufacturers to shift their production to make these PPE equipment to alleviate this crisis around the world. For example, Loreal has started the production of hand sanitizers; Steel bird an Indian motorcycle helmet manufacturer produced face shields, and Noma sei, a luxury shoe brand produced masks. Kumar et al., (2020)examined the covid-19 impact on sustainable production and consumption.

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DOI: 10.22034/ijsom.2021.108791.1947

Ivanov (2020)predicted the impacts of epidemic outbreaks on global supply chains. Belhouideg (2020) investigated the impact of printed medical equipment on the management of the covid-19 pandemic. Paul & Chowdhury (2020) discussed a production recovery plan in manufacturing supply chains for a high-demand item during covid-19. Rowan & Laffey (2020) highlighted the challenges and solutions for addressing the critical shortage of PPE. Belhadia et al. (2020)explored the manufacturing and service supply chain resilience to the pandemic. Ivanov et al. (2017) reviewed the existing research on disruption recovery in the supply chain. Shokrani et al. (2020) discussed the alternative of existing supply chains and with the help of a case study of the face shield.

In the manufacturing systems, the constant production rate has been explicitly assumed by numerous researchers. However, such an assumption holds good only for the products when the demand of the product is known with certainty. The demand of the product is highly sensitive to various factors such as price, production, etc. In this covid-19 pandemic, the demand of medical and PPE equipment has risen rapidly for which the traditional manufacturers are not prepared. Thus, due to the rapid increase in the demand, the manufacturers are now struggling to modify their production. Hence, because of the variability in the production process, the effect of volume agility can't be ignored in such a scenario. Initially, a theory on flexibility in the production process is introduced by Sethi&Sethi (1990). S. Sana & Chaudhuri (2006) investigated a scenario for a decaying product under the assumption of a flexible production rate. Ouyang et al. (2008) explored the optimal strategy for an integrated model with a variable production rate. AlDurgam et al. (2017) investigated the impact of variable production rates on the supply chain with stochastic demand. Sarkar et al. (2018) explored the effect of variable production rates on the quality of products in an integrated scenario. Ruidas et al. (2019) studied an EPQ model with stock and price-sensitive demand and variable production rate in an interval environment. Kamna et al. (2020) discussed the sustainable inventory policy for an imperfect production system with energy usage and volume agility. Alkahtani et al. (2020) optimized resources and carbon emission for non-perishable corps with a variable production rate. Thus, volume agility is an effective tool to deal with this situation efficiently and it is reasonable to assume the production rate as a decision variable rather than a constant parameter.

The growing concern towards environmental issues and sustainable development is receiving great attention of researchers worldwide. During this crisis, the environmental considerations were understandably side-lined. Although environmental protection could not be the priority in this critical situation but it is still important to recognize the problem. Due to the massive production of PPE (e.g. masks, face shields, gloves, hand sanitizer, etc.), a large amount of waste is also generated which is a major environmental issue. Therefore, the sustainable aspect of the production model is explored by incorporating the carbon emissions during the production and inventory storage. Metcalf (2009) discussed the different market-based policy options to control GHG emissions. Čuček et al. (2012) reviewed the literature of footprint analysis for monitoring impacts on sustainability. Chen et al. (2013) considered the EOQ model with different carbon constraints to reduce emissions. He et al. (2015) investigated the impact of two carbon regulations on the lot size and emissions. Klemeš, Van Fan, & Jiang (2020) discussed the impact of protective measures on environmental footprints.(Khanna & Yadav (2020) explored the different carbon policies on an inventory system. Klemeš, Van Fan, Tan, et al. (2020) discussed medical plastic waste management in order to reduce GHG footprints during covid-19.

Due to the covid-19 outbreak, the advertisements on different media can surely prove out to be an effective approach to make the people aware of the products provided by the manufacturers. Since many non-traditional manufacturers have also started the production of PPE, therefore they need to make the public aware about the same. The awareness can be created through advertisements on different traditional and new media platforms. Manufacturers not only promote their products but also keep the public updated about the importance of preventive measures. Nevertheless, besides traditional media, the role of social media is also significant because keeping pace with technology is an essential strategy for public persuasion and awareness. The efforts of the advertising media and sales team encourage the customers to buy the medical equipment in a limited amount in order to avoid shortages in the current scenario. The marketing effort affects the market demand of the supply chain, hence the marketing effort is treated as a decisive factor. The impact of traditional advertising on the demand of the product is initially studied by Goyal & Gunasekaran (1995). Later, how the demand is influenced by advertising media and the salesman's effort is discussed by S. S. Sana (2010) and Chowdhury et al. (2014). Zenetti& Klapper (2016) measured the effects of advertising on consumer's purchase decisions. Further, Kozlenkova et al. (2015) discussed the role of marketing channels in supply chain management. Cárdenas-Barrón& Sana (2015) investigated an integrated scenario where demand varies with the promotional effort. Md Mashud& Hasan (2019) proposed a model for decaying products with the frequency of advertisement and price under shortages. Navarro et al. (2020) discussed a collaborative EPQ model with multiple products with the effect of a marketing effort on demand. Table 1 shows the comparison of the current research with the existing research in the related field.

**Table 1.** Review of existing and current research

| Author(s) | Advertisement dependent demand | Production | Volume agility | PPE | Carbon Emission |
|---|---|---|---|---|---|
| (Ouyang et al., 2008) | | Y | Y | | |
| (Metcalf, 2009) | | | | | Y |
| (Čuček et al., 2012) | | | | | Y |
| (Chen et al., 2013) | | | | | Y |
| (He et al., 2015) | | Y | | | Y |
| (Cárdenas-Barrón& Sana, 2015) | Y | Y | | | |
| (Kozlenkova et al., 2015) | Y | | | | |
| (Zenetti&Klapper, 2016) | Y | | | | |
| (AlDurgam et al., 2017) | | Y | Y | | |
| (Sarkar et al., 2018) | | Y | Y | | |
| (Ruidas et al., 2019) | | Y | Y | | |
| (Ivanov, 2020) | | | | Y | |
| (Paul & Chowdhury, 2020) | | Y | | Y | |
| (Klemeš, et al 2020a) | | | | Y | Y |
| (Navarro et al., 2020) | Y | Y | | | |
| (Shokrani et al., 2020) | | Y | | Y | Y |
| (Alkahtani et al., 2020) | | Y | Y | | Y |
| (Belhadia et al., 2020) | | Y | | Y | |
| This paper | Y | Y | Y | Y | Y |

***Research gap and our contribution***

The present study fulfills the existing research gap by formulating a sustainable production model for personal protective equipment (PPE) incorporating all the above-mentioned aspects i.e., volume agility, advertisement dependent demand, and carbon emission. The COVID-19 pandemic is having an unprecedented impact on societies all over the world. To prevent the spread of the virus, governments have introduced various measures such as travel restrictions, social distancing, and use of personal protective equipment, etc. Surging demand of PPE partly joined with panic buying amid the covid-19 is disrupting global supply and putting lives at risk. The dramatic rise in demand for PPE has depleted stockpiles and led to production backlogs in fluffing demands. Thus, the surge in demand motivates the non-traditional manufacturers to shift their production process to the medical and PPE to survive in this crisis. Hence, volume agility is considered to manage the flexible production process. Moreover, advertisements are an essential ally of spreading awareness, and media plays a mediating role between the public and manufacturers. Advertising efforts encourage the customers to buy in a limited amount to avoid shortages. It is observed that advertising effort influences the customer's decision, and thus the demand is assumed to be dependent on advertisement. Further, due to this pandemic environmental concerns can be sidelined but can't be ignored. However, as the pandemic continues, the excess production of PPE leads to a significant amount of GHG emissions and waste in the environment. Therefore, the environmental aspect is considered through the incorporation of carbon-emission while production and storage of goods. The main aim of the paper is to maximize the total profit by optimizing the cycle time, advertisement cost, and production rate. Some significant managerial insights have been explicated from numerical and sensitivity analysis. To restate, the present study addresses the following research questions:

- What are the optimal strategies to deal with the increasing demand of PPE amid COVID-19?
- What would be the impact of volume agility and advertisement dependent demand on the inventory policy?

- What will be the optimum production rate, advertisement cost, and total profit for a sustainable production model?
- What will be the effect of different model parameters on the optimal production policy?

## 2. Notations

Following are the notations that are used in the model:

$t_1$ = Time where the production stops (months)
$h$ = Storage cost of the item (\$/unit/unit time)
$K$ = Setup cost per order(\$/order)
$\mu$ = Cost of material per unit (\$/unit)
$g$ = Labor and energy cost(\$)
$\delta$ = Tool/ die cost(\$)
$I_m$ = Maximum inventory level in a cycle at $t_1$ (units)
$e_1$ = Amount of emission per production run due to setup(kg/time)
$e_2$ = Average emission per unit of production during production process(kg/time)
$e_3$ = Average emission per unit of production run time generated due to machining operation (kg/time)
$e_4$ = Average emission per unit item per unit time for holding(kg/time)
$e_p$ = Carbon emission cost in production(\$/kg)
$e_h$ = Carbon emission cost in holding (\$/kg)
$s$ = Selling price (\$)
$D(A)$ = Rate of demand as a function of advertisement cost (units/ unit time)
$a$ = Demand function intercept
$b$ = Demand sensitivity parameter related to the advertisement
$\beta$ = Sensitive parameter for advertisement cost

***Decision variable***

$T$ = Time where the inventory cycle end (months)
$P$ = Production rate
$A$ = Advertisement cost (\$/unit)

## 3. Assumptions

The assumptions of this model are listed as:

1. The rate of demand $D(A)$ is a function of advertisement A, and is given as:
$$D(A) = a + bA^{\beta} \tag{1}$$
Here $a, b > 0$ and $0 < \beta < 1$ is scale and shape parameter, and both are positive known constants.
2. The production rate $P$ is flexible, where $P$ is greater than the demand rate.
3. The unit production cost $\chi(P) = \left(\mu + \frac{g}{P} + \delta P\right)$ where $\mu, g, \delta$ are all positive constants. As $\mu$ per unit item is fixed. As per $P$ is rises, some costs like labor costs are similarly circulated over a big quantity of units. Later the cost of production per unit $\left(\frac{g}{P}\right)$ declines as the rate of production $(P)$ rises. The third item $(\delta P)$ linked with tool/die costs is proportionate to the rate of production.
4. The lead time is zero and scarcities are not allowed.

5. Instantaneous replenishment rate with zero lead-time.
6. Emissions of carbon are caused due to production and inventory holding.

## 4. Mathematical model

Consider an inventory system where a production model is formulated with a variable production rate. Demand is advertisement dependent and carbon emissions cost is incurred in production and inventory holding. By using the above-mentioned assumptions, the inventory scenario is shown by fig.1.The cycle includes production and non-production time. The cycle begins at time t = 0 with no inventory and rises till $t_1$ at a rate $P$ and concurrently reduces due to demand. During $(t_1, T)$, the inventory diminishes only due to the demand rate. Finally, the inventory exhausts at time $T$ .

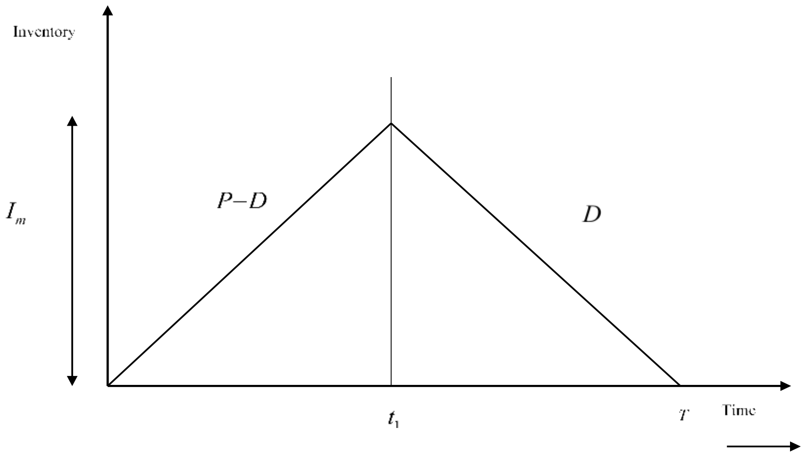



**Figure 1.** Graphical representation of the inventory scenario

The inventory differential equation $I(t)$ at time $t$ in $[0, T]$ is:

$$\frac{dI_1(t)}{dt} = P - (a + bA^{\beta}), \qquad 0 \le t \le t_1 \tag{2}$$

$$\frac{dI_2(t)}{dt} = -(a + bA^{\beta}), \qquad t_1 \le t \le T \tag{3}$$

Using condition $I_1(0) = 0$ and $I_1(t_1) = I_m$ in eq. (2)

$$I_1(t) = Pt - at - btA^{\beta} \tag{4}$$

$$I_m = t_1(\text{P-a-bA}^{\beta}) \tag{5}$$

Using condition $I_2(T) = 0$ and $I_2(t_1) = I_m$ in eq. (3)

$$I_2(t) = (a + bA^{\beta})(T - t) \tag{6}$$

$$I_m = (a + bA^{\beta})(T - t_1) \tag{7}$$

Consequently, from equation (5) and (7)

$$t_1 = \frac{T}{P}(a + bA^{\beta}) \quad (8)$$

Total average inventory is

$$AI = \int_0^{t_1} I_1(t)dt + \int_{t_1}^{T} I_2(t)dt$$

$$= (\text{P-a-bA}^{\beta})\frac{t_1^2}{2} + (a + bA^{\beta})[\frac{T^2}{2} - Tt_1 + \frac{t_1^2}{2}] \quad (9)$$

The carbon emission in production and inventory holding is

$$CE = (Pt_1e_2 + e_1 + e_3t_1) + e_4\{(\text{P-a-bA}^{\beta})\frac{t_1^2}{2} + (a + bA^{\beta})[\frac{T^2}{2} - Tt_1 + \frac{t_1^2}{2}]\} \quad (10)$$

Now, the total profit of the inventory system is given by:

The total profit = “sales revenue - production cost – setup cost - holding cost - advertisement cost – carbon emission cost due to production - carbon emission cost due to holding”.

The various components of the total profit equation are calculated as follows:

Sales Revenue is $R = sT(a + bA^{\beta})$ (11)

***Setup cost :***

The initial cost required to run the production system. It is a fixed cost and dependent on time, the setup cost of the production model is:

$$OC = K \quad (12)$$

***Production cost :***

The cost incurred in the production process, it includes machining and processing cost, labor cost, and tool/die cost. The production cost in the model is given as:

$$PC = (\mu + \frac{g}{P} + \delta P)\int_0^{t_1} Pdt$$

$$= Pt_1(\mu + \frac{g}{P} + \delta P) \quad (13)$$

***Holding cost:***

The holding cost is needed for proper storage of products to control their spoilage/deterioration. Thus, the manufacturer incurs the inventory holding cost for the maintenance of products in stock. It is calculated for the proposed model as:

$$HC = h\{(\text{P-a-bA}^{\beta})\frac{t_1^2}{2} + (a + bA^{\beta})[\frac{T^2}{2} - Tt_1 + \frac{t_1^2}{2}]\} \quad (14)$$

***Advertisement cost:***

In order to create awareness, advertisements on different social media platforms are an effective strategy to reach out to the maximum customers. The advertisement cost is given as:

Advertisement cost $AC = A^{\beta}$ (15)

Due to the massive production of PPE and the storage of them, carbon emissions are produced in the environment. Thus, carbon emission cost due to production and inventory holding is given as:

***Carbon emission cost due to production:***

$$C_1 = e_p(Pt_1e_2 + e_1 + e_3t_1) \tag{16}$$

***Carbon emission cost due to holding:***

$$C_2 = e_he_4\{(\text{P-a-bA}^{\beta})\frac{t_1^2}{2} + (a + bA^{\beta})[\frac{T^2}{2} - Tt_1 + \frac{t_1^2}{2}]\} \tag{17}$$

Using equations (11)-(17) ***Total profit per unit time is:***

$$TP(P, A, T) = \frac{1}{T}[sT(a + bA^{\beta}) - K - Pt_1(\mu + \frac{g}{P} + \delta P) - h\{(\text{P-a-bA}^{\beta})\frac{t_1^2}{2} + (a + bA^{\beta})[\frac{T^2}{2} - Tt_1 + \frac{t_1^2}{2}]\}$$
$$-A^{\beta} - e_p(Pt_1e_2 + e_1 + e_3t_1) - e_he_4\{(\text{P-a-bA}^{\beta})\frac{t_1^2}{2} + (a + bA^{\beta})[\frac{T^2}{2} - Tt_1 + \frac{t_1^2}{2}]\}]$$
(18)

## 5. Solution Procedure

The total profit function is a function of two variables *P, A,* and *T*. Thus, in order to establish optimality following necessary and sufficient conditions must be satisfied:

Necessary conditions:

Now, to establish the optimality of equation (18) the necessary conditions are:

$$\frac{\partial TP(P, A, T)}{\partial P} = 0, \frac{\partial TP(P, A, T)}{\partial T} = 0, \frac{\partial TP(P, A, T)}{\partial A} = 0$$

$$\frac{\partial TP(P, A, T)}{\partial P} = -(\frac{t_1(4\delta P + e_4e_ht_1 + 2(\mu + e_2e_P)) + 2h}{2T}) = 0 \tag{19}$$

Solving the equation (19) we get $P^*$

$$P^* = -(\frac{e_4e_ht_1^2 + (2\mu + 2e_2e_P)t_1 + 2h}{4\delta t_1}) \tag{20}$$

$$\frac{\partial TP(P, A, T)}{\partial T} = -\{(\frac{1}{2T^2})((e_4e_h + h)(a + bA^{\beta})T^2 - 2(A^{\beta} + hP + K) - e_4e_ht_1^2P$$
$$-2(\delta P^2 + \mu P + e_2e_PP + e_3e_P + g)t_1 - 2e_1e_P)\} = 0$$
(21)

$$\frac{\partial TP(P, A, T)}{\partial A} = \{(\frac{1}{2T})[(bT((e_4e_h + h)(2t_1 - T) + 2s) - 2)\beta A^{\beta-1}]\} = 0 \tag{22}$$

Since the equation (21) is a highly complex function in *T* and equation (22) highly complex function in *A*, thus it is difficult to get a closed-form solution for $T^*$ and $A^*$.

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

$$H = \begin{bmatrix} \frac{\partial^2 TP}{\partial T^2} & \frac{\partial^2 TP}{\partial T \partial P} & \frac{\partial^2 TP}{\partial T \partial A} \\ \frac{\partial^2 TP}{\partial P \partial T} & \frac{\partial^2 TP}{\partial P^2} & \frac{\partial^2 TP}{\partial P \partial A} \\ \frac{\partial^2 TP}{\partial A \partial T} & \frac{\partial^2 TP}{\partial A \partial P} & \frac{\partial^2 TP}{\partial A^2} \end{bmatrix}$$ and

$$H_1 = \frac{\partial^2 TP}{\partial T^2} < 0, \qquad \mathrm{H}_2 = \begin{vmatrix} \frac{\partial^2 TP}{\partial T^2} & \frac{\partial^2 TP}{\partial T \partial P} \\ \frac{\partial^2 TP}{\partial P \partial T} & \frac{\partial^2 TP}{\partial P^2} \end{vmatrix} > 0$$

$$H_3 = \det H = \begin{vmatrix} \frac{\partial^2 TP}{\partial T^2} & \frac{\partial^2 TP}{\partial T \partial P} & \frac{\partial^2 TP}{\partial T \partial A} \\ \frac{\partial^2 TP}{\partial P \partial T} & \frac{\partial^2 TP}{\partial P^2} & \frac{\partial^2 TP}{\partial P \partial A} \\ \frac{\partial^2 TP}{\partial A \partial T} & \frac{\partial^2 TP}{\partial A \partial P} & \frac{\partial^2 TP}{\partial A^2} \end{vmatrix} < 0$$

where $H_1, H_2, and\ \mathrm{H}_3$ are the minors of the Hessian matrix $H$ .For the values of $H_1, H_2, and\ \mathrm{H}_3$ , refer to Appendix A.

## 6. Numerical Analysis

The developed model is demonstrated using a numerical example. The following parameter values should be taken in appropriate units for numerical illustration:

**Table 2.** Parameter values

| | | | |
|---|---|---|---|
| $a$ | 100 | $e_3$ | 4 kg/time |
| $b$ | 60 | $e_4$ | 2 kg/time |
| $\beta$ | 0.04 | $e_P$ | $2/kg |
| $h$ | $2/unit/time | $e_h$ | $1/kg |
| $s$ | $200 | $\mu$ | $2 |
| $K$ | $600/order | $g$ | $1000 |
| $e_1$ | 2 kg/time | $\delta$ | $0.001 |
| $e_2$ | 0.5 kg/time | | |

Using **Table 2** numerical data the optimal results are obtained as follows:

Production rate $P^*$ = 1000units, Replenishment cycle time $T^*$ = 2.813 months, Advertisement cost $A^\beta$ = $1742.231and Total Profit $TP$ = $33600.896.

***Comparative Analysis***

In this COVID-19 pandemic scenario, the demand of medical and PPE has risen drastically for which the governments and manufacturers both are not prepared. Due to the surge in demand, the manufacturers have increased their production, but it is not sufficient to cope up with the demand. Generally, the production rate is assumed to be constant, but to deal with the fluctuating demand the present study considers the volume flexibility (i.e., variable production rate) which is pertinent to deal with this crisis. Further, carbon emission is considered to address the environmental imbalance. Moreover, to illustrate the significance of volume agility in inventory modelling, a comparative analysis of the present model is done with the case when volume agility is not implemented. The results are presented in Table 3.

**Table 3.** Comparative results for different cases: with and without volume agility

| | With volume agility | Without volume agility |
|---|---|---|
| Total Profit ( $TP$ ) | $33600.896 | $33511.742 |

| | | |
|---|---|---|
| Advertisement cost ( $A$ ) | \$ 1742.231 | \$ 1633.369 |
| Replenishment time ( $T$ ) | 2.813 months | 2.653 months |
| Production rate ( $P$ ) | 1000units | 1500 units |
| Production time ( $t_1$ ) | 0.508 month | 0.319 month |

It is evident from the findings of Table 3 that the implementation of volume agility is more beneficial in comparison to the one without it. The profit of the model with the volume agility is \$33600.896 and the advertisement cost is \$1742.231. However, the profit without the volume agility is \$33511.742 and the advertisement cost is \$1633.369. Although the investment in the advertisement is an additional expense for the manufacturer, but it helps to increase the demand and consequently profit. Further, it is favourable for the producer to have a flexible production rate to avoid over/ under production as it increases the total profit. Thus, it can be stated that adjusting the production rate by implementing volume agility and investment in the advertisement is an effective strategy to sustain in this economic and health crisis.

## 7. Sensitivity Analysis

Sensitivity analysis has been performed to study the effect of key parameters such as demand parameters $(a)$ and $(b)$ , the parameter for advertisement cost ($\beta$), holding cost ($h$), carbon emission cost in production ($e_P$), carbon emission cost in holding ($e_h$) and material cost ($\mu$) on the optimal solution. Results have been recorded in Table 4. Moreover, Table 5 demonstrates the graphical representation of various parameters on total profit (based on the numerical data of table 4).

**Table 4.** Sensitivity analysis of the parameters

| Parameters | | T | A | CE | TP |
|---|---|---|---|---|---|
| | 90 | 2.915 | 1805.147 | 2203.954 | 31688.1 |
| | 95 | 2.863 | 1772.795 | 2139.898 | 32644.04 |
| | 100 | 2.813 | 1742.231 | 2193.565 | 33600.9 |
| | 105 | 2.767 | 1713.305 | 2189.674 | 34558.18 |
| a | 110 | 2.723 | 1685.945 | 2186.61 | 35516.03 |
| | 10 | 2.657 | 1357.705 | 1869.13 | 31033.28 |
| | 15 | 2.736 | 1545.594 | 2028.115 | 32313.97 |
| | 20 | 2.813 | 1742.231 | 2193.56 | 33600.9 |
| | 25 | 2.89 | 1947.534 | 2365.413 | 34893.65 |
| b | 30 | 2.967 | 2161.502 | 2543.723 | 36191.9 |

**Table 4.** Continued

| Parameters | | T | A | CE | TP |
|---|---|---|---|---|---|
| | 0.02 | 2.01 | 525.905 | 1242.331 | 31636.44 |
| | 0.03 | 2.367 | 1006.468 | 1630.605 | 32535.29 |
| | 0.04 | 2.813 | 1742.231 | 2193.56 | 33600.9 |
| | 0.05 | 3.361 | 2865.208 | 3010.628 | 34854.38 |
| $\beta$ | 0.06 | 4.023 | 4566.893 | 4194.447 | 36326.51 |
| | 1 | 3.566 | 2232.206 | 3189.748 | 33835.01 |
| | 1.5 | 3.137 | 1952.427 | 2600.892 | 33710.94 |
| | 2 | 2.813 | 1742.231 | 2193.56 | 33600.9 |
| | 2.5 | 2.56 | 1578.267 | 1896.8 | 33501.61 |
| h | 3 | 2.355 | 1671.873 | 1671.873 | 33410.87 |
| | 1 | 2.816 | 1748.651 | 2196.769 | 33692.77 |
| | 1.5 | 2.815 | 1745.45 | 2195.163 | 33646.83 |
| | 2 | 2.813 | 1742.231 | 2193.56 | 33600.9 |
| | 2.5 | 2.812 | 1739.036 | 2191.965 | 33554.96 |
| $e_P$ | 3 | 2.811 | 1735.845 | 2190.363 | 33509.03 |
| | 0 | 5.054 | 3213.417 | 5670.251 | 34148.84 |
| | 0.5 | 3.566 | 2232.214 | 3189.705 | 33835.01 |
| | 1 | 2.813 | 1742.231 | 2193.56 | 33600.9 |
| | 1.5 | 2.355 | 1446.567 | 1671.853 | 33410.87 |
| $e_h$ | 2 | 2.045 | 1247.656 | 1354.865 | 33249.09 |
| | 1 | 2.822 | 1757.387 | 2204.518 | 33781.78 |
| | 1.5 | 2.818 | 1749.798 | 2199.033 | 33691.34 |
| | 2 | 2.813 | 1742.231 | 2193.56 | 33600.9 |
| | 2.5 | 2.809 | 1734.685 | 2188.093 | 33510.46 |
| μ | 3 | 2.805 | 1727.158 | 2182.642 | 33420.04 |

**Table 5.** Graphical representation of different sensitivity parameters

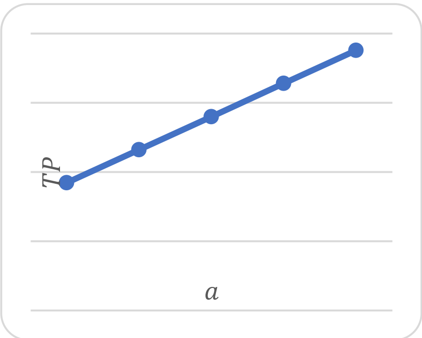



**Fig. 2 Effect of demand parameter $(a)$ w.r.t total profit $(TP)$**

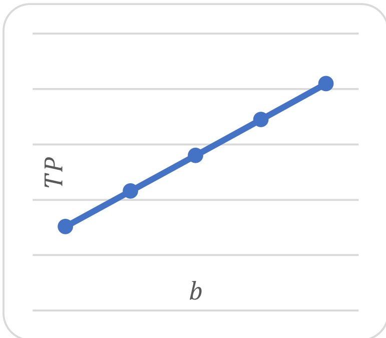
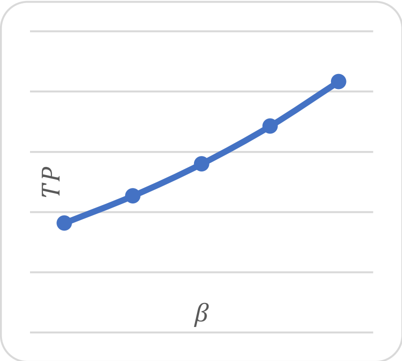
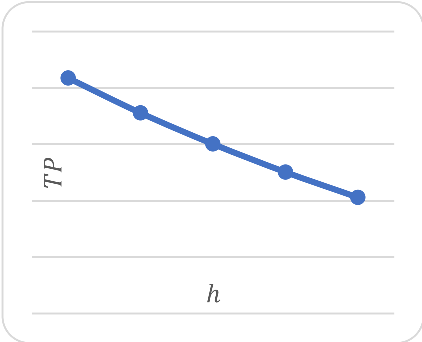
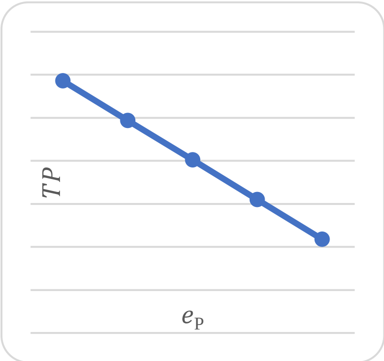
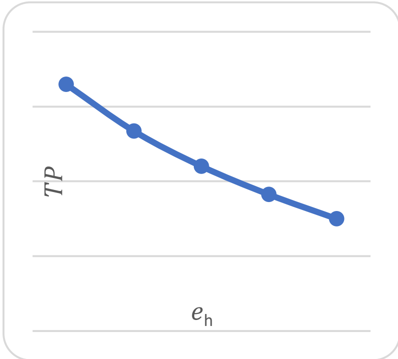
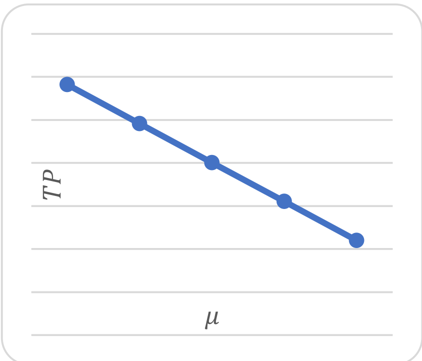



**Fig. 3 Effect of demand parameter $(b)$ w.r.t total profit $(TP)$**

**Table 5.** Continued

| | |
|---|---|
| <br>**Fig. 4 Effect of demand parameter $(\beta)$ w.r.t total profit $(TP)$** | <br>**Fig. 5 Effect of demand parameter $(h)$ w.r.t total profit $(TP)$** |
| <br>**Fig. 6 Effect of demand parameter $(e_p)$ w.r.t total profit $(TP)$** | <br>**Fig. 7 Effect of demand parameter $(e_h)$ w.r.t total profit $(TP)$** |
| <br>**Fig. 8 Effect of demand parameter $(\mu)$ w.r.t total profit $(TP)$** | |

### 7.1 Observations and Managerial insights

From Table 4, the following observations and managerial insights are made:

- When the scaling factor of demand ($a$) increases, the advertisement cost $(A)$ and the cycle length ($T$) decreases, whereas the total profit increases. A higher value of ($a$) helps to increase the demand which leads to an increase in revenue and hence profit. Amplified demand puts pressure on the production process which also affects carbon emissions ($CE$) negatively. This happens due to a high surge in demand, which further suggests to invest less in the advertisement.

- Also, an increase in the demand parameter $(b)$ gives a boost to demand, thus the total profit ($TP$) and the cycle length ($T$) increases significantly. High demand can be pulled by investing more in the advertisement sector which implies more investment in the advertisement, thus the cost increases significantly. Moreover, the production rate increases to satisfy the surge in demand, at the same time carbon emission increases significantly due to the increase in production rate. Thus, it clearly indicates that although investment in the advertisement is an additional expense for the manufacturer, but it helps to increase the demand and profit.

- With a rise in the effectiveness parameter of advertisement cost ($\beta$), there is a steep rise in demand which leads to higher profits. Moreover, production cycle time ($T$) increases in order to satisfy the rising demand which ultimately leads to carbon emissions ($CE$). Since the effectiveness of the advertisement can be enhanced by increasing the investment in marketing efforts, thus the advertisement cost escalates.

- With an increase in holding cost ($h$) the advertisement cost $(A)$, the cycle length ($T$), and the total profit ($TP$) decreases. Increased holding cost ($h$) indicates that the production quantity must be watched carefully and the only required amount must be produced. It is suggested to reduce the production time to deal with increasing holding costs.

- An increase in carbon emission cost of production ($e_P$) contributes to the total cost component which obviously affects the total profit ($TP$) unfavourably. However, the cycle length ($T$), the advertisement cost $(A)$, and the carbon emissions ($CE$) decrease slightly. It is suggested to do shorten the production cycle so as to decrease the machine run time and thereby emit smaller amount of emissions in the environment.

- With an increase in carbon emission cost of holding ($e_h$) the total profit ($TP$), cycle length ($T$), the advertisement cost $(A)$, and the carbon emissions ($CE$) decrease. It is suggested to make sure that only the required quantity is produced and stored in the system

- The increase in material cost ($\mu$) of production increases the total cost due to which the profit decreases. The increase in the cost implies that the production of the requisite quantity should take place along with the machine processing time. As the cycle length ($T$), the advertisement cost $(A)$, and the carbon emissions ($CE$) decrease, it is suggested to decrease the production time to deal with the material cost of production.

## 8. Concluding remarks

### 8.1. Conclusion

The COVID-19 pandemic has been one of the most severe supply chain disruptions in recent times. The rise in the demand of PPE motivates the manufacturers to modify their production to meet the demand, thus a flexible production process is considered to depict a more realistic model. Further, while traditional manufacturers ramp up their production, but still are unable to manage the demand in this pandemic. So, the government has encouraged the non-traditional manufacturers to shift their production to make PPE to alleviate this crisis. Moreover, for the non-traditional manufacturers, it is necessary to promote their product and also aware the public about the preventive measures. Thus, an investment in the advertisement is necessary, which also has an impact on the demand. Further, the waste and GHG emission generated by the massive production of PPE is a concern for the environment which is not the priority in the current situation but cannot be overlooked. Thus, the sustainability of the model is considered by incorporating carbon emissions in the production process and inventory holding. Motivated by this, a sustainable production model is developed with volume agility and advertisement dependent demand. The objective of the proposed article is to optimize the production rate, advertisement cost, and cycle time intending to maximize the total profit. Further, a comparative numerical analysis of the present model is done with a model without volume agility to highlight the significance of volume agility. Some important managerial insights are obtained from sensitivity analysis that would assist the manufacturers in optimal decision-making under varying parameter values. The key findings of the paper are concluded as:

- Advertisement helps to boost the demand and also results in a considerable increase in total profit for the manufacturer. Moreover, it spreads awareness among the masses about the preventive measures to sustain this economic and health crisis.
- The incorporation of volume agility enables the manufacturers to deal with fluctuating demand efficiently.
- For higher holding costs, it is suggested to reduce the production time so as to manage the inventory effectively.
- The environmental aspects are taken into consideration by implementing the carbon-emissions during the inventory storage and production process. In order to reduce the emissions, the CE cost may be increased.
- Comparative analysis suggests that the model with volume agility performs better than the one without the volume agility.

### 8.2 Future directions and limitation

For future studies, the present model can be extended for the complete and partial backlogging. Other possible extensions may include rework and waste management of the medical waste, hospital waste, etc. Further, analyzing the effect of price and time-dependent holding costs also a good extension. The presence of imperfect items, their screening is another challenge during the crisis. Moreover, the effect of the pandemic on production firms under the scenario of multi-echelon supply chains and multiple inspections can be studied. The focus of the study is limited to the medical and personal protective equipment PPE. Future researchers may consider essential items, food products, perishable products to enhance their research.

**Acknowledgment**
The authors deeply appreciate the editor and the anonymous reviewers for their valuable comments and suggestions to improve the quality of the research paper. The corresponding author would like to thank the University of Delhi, Delhi for funding this work through the Faculty Research Programme (FRP) of the IoE scheme under the grant number IoE/2021/12/FRP.

**Conflicts of Interest**
On behalf of all authors, the corresponding author states that there is no conflict of interest.

**Appendix A**

$$\frac{\partial^2 TP(P,A,T)}{\partial T^2} = \{(\frac{1}{T^3})(-2(A^{\beta}+hP+K)-(Pt_1^2 e_h e_4)-2(\delta P^2+\mu P+Pe_2e_P+e_3e_P+g)t_1-2e_1e_P)\} \tag{23}$$

$$\frac{\partial^2 TP(P,A,T)}{\partial P^2} = -(\frac{2\delta t_1}{T}) \tag{24}$$

$$\frac{\partial^2 TP(P,A,T)}{\partial A^2} = \{(\frac{1}{2T})[(bT((e_4e_h+h)(2t_1-T)+2s)-2)(\beta-1)\beta A^{\beta-2}]\} \tag{25}$$

$$\frac{\partial^2 TP}{\partial T\partial P} = \frac{\partial^2 TP}{\partial P\partial T} = -(\frac{-t_1(e_4e_ht_1+4\delta P+2(\mu+e_2e_P))-2h}{2T^2}) \tag{26}$$

$$\frac{\partial^2 TP}{\partial T\partial A} = \frac{\partial^2 TP}{\partial A\partial T} = -\{\frac{\beta A^{\beta-1}(b(e_4e_h+h)T^2-2)}{2T^2}\} \tag{27}$$

$$\frac{\partial^2 TP}{\partial P\partial A} = \frac{\partial^2 TP}{\partial A\partial P} = 0 \tag{28}$$

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