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Emergency order allocation of e-medical supplies due to the disruptive events of the healthcare crisis

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ABSTRACT

The availability of electronic (e-medical) homecare essentials, such as thermometers, oximeters, and oxygen concentrators during the peaks of the pandemic coronavirus disease (COVID-19), has been witnessed as critical in saving the lives of people across the world. This paper presents a supply order allocation strategy of e-medical homecare essentials (HCEs) in a multi-supplier environment by a distributor while ensuring sufficient and timely availability for emergency consumption during pandemic peaks. The results, based on the actual demand data of HCEs obtained from a regional HCE distributor during the pandemic peak of the second wave in India, i.e. April-May 2021, suggest that a minimum (maximum) average of 94% (98%) availability of e-medical HCEs respectively at pharmacies could be achieved during the peak demand period using the proposed emergency order allocation algorithm in this study. Conclusively, the analysis of this study could generate insightful implications for emergency operations decisions in the HCEs supply-distribution channel.

1. Introduction

Disruptive events such as the deadly coronavirus disease (COVID-19) and the Ukraine-Russia war have exposed the entire world to the worst of humanity and human life experiences. The double-edged sword of repeated COVID-19 infection waves and Ukraine-Russia has brought the critical supply chains of healthcare supplies to a new low (Gleeson, 2022; Partida, 2022). The world has witnessed the worst COVID-19 impact on India and South Africa, where thousands of people died in a very short span of time. The quick spread of the virus, along with the limited supply of oxygen and medical essentials, led to a panic situation in India, resulting in many deaths across the country (Kuppalli et al., 2021).

Kuppalli et al. (2021) suggested that the international community should support the Indian government in procuring e-medical supplies for medical homecare essentials (HCEs) during the disastrous crisis of the second wave of COVID-19 in April-May 2021. The government took extraordinary steps to control the situation with the help of industrialists, non-governmental organizations (NGOs), and many other self-help groups to promote homecare instead of hospital visits (Ayog, 2021). However, the panic in the air led to a beeline accumulation of people at pharmacies to buy e-medical devices such as thermometers, pulse oximeters, temperature guns, and costly oxygen concentrators; these were considered to be the essentials for homecare for COVID-19 patients (Business-Standard (BS), 2021). It was hoped that the usage of e-medical HCEs would prove to be a great help to patients and countries with limited healthcare infrastructure (Mondal & Mondal, 2021).

Moreover, the disruptions to global supply chains led to a shortage of HCE products and increased panic buying behavior (Chauhan et al., 2022; Choi, 2021; Raj et al., 2022). Panic buying of e-medical homecare essentials was substantiated by disrupted supply chains leading to longer lead times; this resulted in the unprecedented acute shortage of HCE items in both suppliers and distributors. The limited and uneven distribution of these very critical e-medical homecare essentials had a negative effect on thousands of COVID-19 patients in India. The limited expertise in data-driven decision-making of distributors left them helpless to the inappropriate distribution of HCEs, which eventually impacted the demand fulfillment at retailers (Amankwah-Amoah et al., 2021; Sheng & Saide, 2021).

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Motivated by a lack of theoretical studies into the emergency order allocation mechanism in a disruptive environment, this paper has been developed to address the question - How can a multi-brand distributor of HCEs allocate supply orders of HCEs to multiple suppliers during emergencies such as the COVID-19 pandemic? This paper makes four contributions to the body of knowledge. Firstly, the proposed model helps a multi-brand distributor of HCEs to maintain the availability of HCEs in an emergency like the COVID-19 pandemic. Secondly, the proposed order allocation strategy helps to achieve the desired availability level of HCEs under a pre-determined ordering policy in a COVID-19 environment, thereby ensuring the timely and sufficient fulfillment of HCEs in the demand market. Thirdly, this work considers an actual case of emergency order allocation by a multi-brand HCE distributor located in Northern India to provide a practical application of the proposed model. Fourthly, the present work proposes some developmental suggestions in the context of emergency operations; namely, the distributor should allocate orders based on the supplier’s order fulfillment capability of HCEs.

In summary, this paper contributes to (i) the pandemic-induced disaster operations management literature by investigating a unique emergency order allocation problem and (ii) the COVID-19-induced operations management literature by generating vital managerial insights concerning a multi-brand e-medical HCEs distributor’s emergency order allocation mechanism in a COVID-19 outbreak environment. Additionally, this paper contributes to the literature concerning the order allocation of HCEs to suppliers with timely and sufficient availability in medical stores to stem retail panic-buying behavior. Hence, the present work lays the foundation for future research in the area of pandemic-induced emergency operations.

The rest of this paper is organized as follows. Section 2 outlines the relevant literature. Section 3 elucidates the proposed emergency order allocation strategy and the associated steps for its implementation. Section 4 presents an empirical illustration to highlight the effectiveness of the proposed strategy. Section 5 offers some managerial contributions and policy implications. Section 6 concludes the paper with future research directions.

2. Literature review and research gaps

To address any research gaps and show the theoretical contribution, this section discusses those previous studies examining the supply order allocation strategy of HCEs in a multi-supplier environment by a distributor while ensuring sufficient and timely availability for emergency consumption during pandemic peaks. In this regard, Duijzer et al. (2018) studied the effect of vaccination and found that allocating a unique fraction for a vaccine to treat a population helps to achieve optimal coverage for dose distribution. Anparasan & Lejeune (2019) provided an epidemic response solution algorithm for the 2010 cholera outbreak in Haiti for the deployment of medical staffing teams. Chen et al. (2019) proposed a simulated annealing-based algorithm to optimally allocate medical staff to serious patients subjected to triage requirements. Andersson et al. (2020) developed an optimization model for the allocation of ambulance stations in emergency medical services. Mehrtra et al. (2020) proposed a stochastic optimization model for allocating and sharing a ventilator inventory in the COVID-19 pandemic. Govindan et al. (2020) proposed a decision support system to manage a healthcare supply chain by classifying community members during an epidemic outbreak such as COVID-19. Olivares-Aguilla & ElMaraghy (2020) proposed a system dynamics model to examine the supply chain behavior after full and partial disruptions. Ivanov & Dolgui (2020) studied the viability of intertwined supply networks in increasing the supply chain resilience under a COVID-19 outbreak.

In addition, Choi (2020) highlighted the importance of logistics technology in transforming service operations disrupted by COVID-19. Singh et al. (2020) studied the impact of COVID-19 on logistics systems and disruptions in the food supply chain using simulation. In this VUCA (Volatility, Uncertainty, Complexity, and Ambiguity) world, it is necessary to develop reconfigurable supply chains (Dolgui et al., 2020). Guo et al. (2021) examined the COVID-19 response in China by conceptualizing resilience from the complex adaptive system perspective. Ivanov (2021) highlighted the importance of supply chain viability in the COVID-19 context. COVID-19 has impacted the operations of sustainable production and consumption (Bai et al., 2021; Mofijur et al., 2021). Liu et al. (2021) introduced a new approach to medical supplies scheduling in the public healthcare department to increase the accuracy of supply planning for medical materials, including supply per vehicle for each healthcare department and medical material allocation for each healthcare department. Ling et al. (2021) introduced a new multi-objective optimization approach called multi-objective water wave optimization (WWO) to integrate civilian-military scheduling to supply medical products to increase the availability of medical supplies. This also reduced the total cost of scheduling, leading to a reduction in the rate of reservation of medical supplies for military a new MCDM model to select sustainable suppliers for medical supplies during COVID-19. Moreover, Queiroz et al. (2020) revealed through a structured analysis of literature that the preparedness perspective, which is heavily involved in the planning and distribution of medical supplies, has been a major focus in optimization method-driven studies (Sarigol et al., 2022). With simulation and order allocation algorithms remaining on the backseat, this may have provided a real-time, effective, and quick solution in an epidemic situation. Hence, in our study, we have attempted to fill this gap and propose an emergency order allocation algorithm for the distribution of medical supplies during a pandemic outbreak (Bai et al., 2021; Mofijur et al., 2021).

From the literature review, the following research gaps are identified. Firstly, despite the breadth of work on sourcing and order allocation decisions, the research on emergency sourcing and order allocation decisions is still nascent. Secondly, research on COVID-19-induced emergency supply-distribution management is growing. Thirdly, none of the previous studies on emergency operations management have analyzed the effect of pandemic-induced demand surges of HCE products during COVID-19 lockdowns to facilitate emergency consumption of HCEs in the demand market.

Our work deviates from the extant research on sourcing and order allocation as we consider the dynamics of a pandemic (product availability, demand fulfillment, and profitability) in the model development. Further, unlike previous research that mostly focused on determining the optimal sourcing and order allocation decision based only on profit, this work aims to provide an emergency supply order allocation strategy that ensures the timely and sufficient availability of HCEs in the demand market considering product availability and demand fulfillment as the major objectives; profitability is not the central feature. Thus, this work addresses the above gaps by proposing an empirically supported strategy for a multi-brand distributor of HCEs to ensure the timely availability of HCEs in the demand market for emergency consumption.

3. Emergency supply order allocation

3.1. Problem description

The disruption of the global supply chain created product shortages in India. China implemented strict restrictions to curb the spread of COVID-19, which led to the intermittent supplies of medical essentials in India. Hence, the disruptions in supply chains led to constrained operations in the production (raw material inadequacy) and distribution (transportation issues) of HCEs. During the second wave, the information related to the scarcity of oxygen magnified the problem and further led to the intensification of the issue of uneven distribution of HCEs supplies. The attempts to procure and supply HCEs were restored through some extraordinary majors for HCEs and urgently supplied to the market to control panic and deaths in India.
HCEs are mainly supplied through distributors to pharmacies and surgical equipment suppliers. The pharmacies record the demand data for every product and then communicate it to the medical representative of the multi-brand HCE product distributor on a daily or fortnightly basis. The multi-brand distributor then makes an order through various suppliers to ensure that the availability of HCEs is at least 0.91 to fulfill demand and reduce panic buying. To ensure that the multi-brand distributor is not hoarding the HCEs, the cost of supplies (as set by a supplier) is assumed to vary with each percentage of addition or reduction in supplies. For example, if the multi-brand distributor places an additional 1% quantity to a supplier apart from the contracted supply, then the cost of the supplies will be inflated by a fraction of each unit price. Hence, if a supplier provides an additional ten units along with the pre-ordered 100 units, then the supplier generally charges a higher price for the additional units. However, if a supplier reduces the order below the minimum level (as described above), then the reduction in the price charged per unit to the multi-brand distributor will be 1% for each type of HCE. However, an increment of 3%, 4%, 5%, and 2.5% can be made in HCE prices by the supplier if the multi-brand distributor makes additional requirements for the HCEs. The allocation of minimum orders to the suppliers is important as the multi-brand distributor has pressure from sellers who are aware of the demands of customers for specific HCE products.

### 3.2. Emergency supply order allocation

The emergency order allocation strategy has been designed in consultation with a multi-brand HCE distributor who has been able to meet the availability requirement very effectively during the second COVID-19 wave in India. Table 1 summarizes the notation used in the order allocation mechanism. Allocation of orders made by the multi-brand distributor to its suppliers is based on the suppliers’ capability of on-time fulfillment of the ordered quantity i.e. the supplier’s on-time fulfillment index ($SI_{ij}$). For example, if a supplier meets the demand 80 times out of 100 times, then the on-time fulfillment capability is considered as 80% or indexed as 0.80 on a 10-point scale. The minimum allocation of orders is kept at the level of 10% of the total order i.e.10% of the total order is to be allocated to the supplier with the lowest $SI$ value. An incremental mechanism of order allocation is followed with an additional 5% of orders placed to the next best capable supplier. For example, if four suppliers have $SI$s of 0.70, 0.80, 0.90, and 0.98, then the supplier with $SI = 0.7$ will supply a minimum of 10% of the total order quantity, while the suppliers with $SI = 0.8$ and $SI = 0.9$ will be allocated with 15% and 20% of the total order, respectively. The rest of the order will be placed with the supplier with the highest $SI$ (0.98) i.e. the remaining 55% of the total order. To ensure timely availability of the HCEs in the demand market (pharmacies), the minimum and maximum desired product availability index (AI) for procuring an HCE from a supplier by a multi-brand distributor is set in the range of $AI_{ij} = 0.91$ and $AI_{ij} = 1$, respectively. Specifically, the multi-brand distributor wants to ensure that the availability of HCEs is at least 0.91 to fulfill demand and reduce panic buying. To ensure that the multi-brand distributor is not hoarding the HCEs, the cost of supplies (as set by a supplier) is assumed to vary with each percentage of addition or reduction in supplies. For example, if the multi-brand distributor places an additional 1% quantity to a supplier apart from the contracted supply, then the cost of the supplies will be inflated by a fraction of each unit price. Hence, if a supplier provides an additional ten units along with the pre-ordered 100 units, then the supplier generally charges a higher price for the additional units. However, if a supplier reduces the order below the minimum level (as described above), then the reduction in the price charged per unit to the multi-brand distributor will be 1% for each type of HCE. However, an increment of 3%, 4%, 5%, and 2.5% can be made in HCE prices by the supplier if the multi-brand distributor makes additional requirements for the HCEs. The allocation of minimum orders to the suppliers is important as the multi-brand distributor has pressure from sellers who are aware of the demands of customers for specific HCE products.

### 3.3. Performance measures

This section provides a basic mathematical formulation concerning the proposed emergency order allocation strategy. The fulfillment capability of supplier $i$ is measured as the ability of a supplier to deliver product $j$ on-time. Therefore, the measure for on-time availability of product $j$ that is fulfilled by a set of suppliers can be expressed as:

$$ AI_{ij} = \frac{\sum_{k \in \mathcal{K}} q_{ijk} SI_{ik}}{\sum_{k \in \mathcal{K}} q_{ijk}} \forall j = 1, 2, ..., m; \forall i = 1, 2, ..., n $$

where $AI_{ij}$ is the availability index of product $j$. If $AI_{ij} = 1$, then product $j$ is fulfilled by a set of suppliers.

1 Availability index is a measure that ensures on-time availability of a product that can be fulfilled by a set of suppliers.

2 Based on an interview with a multi-brand distributor during Phase 1 of the COVID-19 lockdown in Haridwar, India.

3 Similar treatments can be seen in Kawtummachai and Van Hop (2005).

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**Table 1**

| Notation  | Definition |
|-----------|------------|
| $AI_{ij}$ | Availability index of product, $j = 1$ to $m$ |
| $q_{ij}$ | Quantity of product $j$ sold to store $i$ |
| $C_{ij}$ | Procurement cost of product $j$ incurred by the distributor |
| $P_{ij}$ | Price of product $j$ charged by the distributor to store $i$ |
| $d_j$ | Quantity of product $j$ charged to supplier $i$ |
| $P_k$ | Price of product $j$ charged by the distributor to supplier $i$ |
| $S_k$ | Profit of the distributor after selling product $j$ |

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**Fig. 1.** HCE product distribution channel in India.
fully available and \( \sum_{i=1}^{n} q_{ij} = 1 \). \( S_{ij} \) is supplier \( i \)'s fulfillment index with respect to product \( j \). Correspondingly, the total daily procurement cost \( C \) of product \( j \) can be represented as:

\[
C_{j} = \sum_{i=1}^{n} \left( \frac{p_{ij} q_{ij} d_{j}}{S_{ij}} \right) \quad \forall j = 1, 2, \ldots, m; \forall i = 1, 2, \ldots, n \tag{2}
\]

The daily revenue generated from product \( j \) for the multi-brand distributor can be written as:

\[
R_{j} = \sum_{i=1}^{n} \left( \pi_{ij} q_{ij} d_{j} \right) \quad \forall j = 1, 2, \ldots, m \quad \forall k = 1, 2, \ldots, l \tag{3}
\]

Accordingly, the daily profit \( \pi_{j} \) after selling the product \( j \) can be obtained using:

\[
\pi_{j} = R_{j} - C_{j} = \sum_{i=1}^{n} \left( \pi_{ij} q_{ij} d_{j} \right) - \sum_{i=1}^{n} \left( p_{ij} q_{ij} d_{j} \right) \tag{4}
\]

### 3.4. Strategy implementation

We propose a strategy for the emergency order allocation of HCEs. Generally, order allocation is a combinatorial optimization problem (Lee, 2004). However, such computationally challenging problems can be solved through a search algorithm or metaheuristic (Cook et al., 1997). Therefore, unlike existing optimization-based models, we propose an empirical strategy for solving the emergency order allocation problem of a multi-brand HCE distributor during the second wave of COVID-19 in India. The empirical strategy seeks to assist the multi-brand HCE distributor in allocating an order of HCEs to HCE suppliers based on its product availability index and supplier’s fulfillment index. The steps for implementation of the proposed strategy are as follows:

Step 1. For each product \( j \), the supplier with minimum \( S_{ij} \) and allocate 10% of the daily demand (i.e. \( q_{ij} = 0.1 \)) to this supplier.

Step 2. Allocate 15% of the daily demand to the next best supplier i.e. an increment of 5% in allocating orders to the next best scoring supplier is made. Specifically, 10% is allocated to the first supplier (with the lowest \( S_{ij} \) value), and an extra 5% of daily demand is allocated to the next best supplier based on the \( S_{ij} \) value.

Step 3. Allocate 20% of the daily demand to the next best supplier i.e. 15% allocated to the second supplier and an extra 5%; 20% of the daily demand is allocated to the next best supplier based on \( S_{ij} \) value.

Step 4. Repeat the above steps until the supplier with the highest \( S_{ij} \) value is left. If, after step 3, only one supplier is left, then allocate all the remaining demand to the final best supplier.

Step 5. Step 1 to step 4 are the steps taken to find the total score using the above incremental ordering policy (10% demand to be allocated to the supplier with the lowest \( S_{ij} \) value, whereas an additional 5% is to be given to each next-best \( S_{ij} \) value supplier). Next, compute \( A_{ij} \) using Eq. (1).

Step 6. To ensure a higher availability index of product \( j \), we vary the % allocation of orders by decreasing 1% each in order from the low \( S_{ij} \) value suppliers and replacing this quantity of the order as an additional order quantity to the supplier with the highest \( S_{ij} \) value. This variation of quantity in order allocation helps in achieving the different values of \( A_{ij} \); this represents the aggregated availability of HCE products received from different suppliers. Along with \( A_{ij} \), this step also provides a mix of the order quantity, showing the total purchase cost and total profit. This provides the distributor with a win-win situation by increasing the social contribution to containing the spread of COVID-19.

Step 7. A simulation is performed on multiple combinations of the order allocation quantity \( q_{ij} \) to find feasible solutions based on \( A_{ij} \) varying from 0.91 to 1. Each combination of the order allocation quantities to the selected suppliers results in a unique \( A_{ij} \) value that reflects how much on-time availability of a product can be made at the incurred total purchase cost if a specific order quantity is placed with a supplier.

The detailed explanation of the algorithm which we have used to perform computer simulation is tested using daily demand data of thermometers during the second wave. The demand data and fulfillment index of the supplier are shown in Tables 2 and 3, respectively.

Using the order allocation mechanism and the proposed solution algorithm, we allocate 10% of the orders, i.e. 500 units, to supplier S4 based on its minimum \( S_{ij} \) value (i.e. 0.5) among all the suppliers as described in Step 1. According to Step 2, 15% of the orders, i.e. 750 units, are allocated to supplier S3 with an \( S_{ij} \) value of 0.8. Similarly, as per Step 3, 20% of the orders, i.e. 1000 units, are allocated to supplier S2. Furthermore, according to Step 4, the remaining 55% of the orders, i.e. 2750 units, are allocated to supplier S1. Hence, based on the order allocation ratios, we can compute the total on-time availability index for thermometers, i.e. \( A_{ij} \) for thermometers is computed as 0.91, the minimum value required for our multi-brand distributor to maintain product availability. Here the \( A_{ij} \) value of 0.91 suggests that if a multi-brand distributor allocates the thermometers orders using a 10%, 15%, and 20% ratio to its suppliers, a 91% availability of thermometers at the distribution center is assured. In other words, the multi-brand distributor may not be able to fulfill 9% of the stores’ demands; this can be critical during a pandemic such as COVID-19. The cost of these allocated orders is shown in Table 3. Hence, the total purchase cost (from Eq. (2)) \( C_{j} \) is INR 267,500. Furthermore, if we perform Step 6 and allocate the percentage of order quantities by reducing from low scorer and adding into a high scorer, i.e. 4% (200 units), 9% (450 units), 14% (700 units), and 73% (3650 units) of the orders to suppliers S4, S3, S2, and S1, respectively, then the \( A_{ij} \) for thermometers increases from 0.91 to 0.955. Accordingly, the total purchase cost (\( C_{j} \)) is INR 269,470. Comparing the two cases, the proposed solution algorithm improves the level of availability of HCEs at a multi-brand distributor in lieu of a small increment in the total purchase cost. In the first case, we had achieved a 91% on-time availability of thermometers and incurred a total purchase cost of INR 2,67,500; whereas, in the second case, we could now achieve an on-time availability of 95.5% with a small increase in the total purchase cost of INR 1970. Hence, the proposed empirical strategy can effectively help the multi-brand distributor to maintain a higher availability of HCEs to meet the demand of the medical stores.

### 4. Empirical illustration

To validate the effectiveness of the proposed order allocation mechanism and the associated solution algorithm, we provide an

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**Table 2**

Demand at medical stores.

| HCE Product | Pharmacy | Quantity |
|-------------|----------|----------|
| Thermometer (P1) | M1 | 750 |
| | M2 | 1000 |
| | M3 | 1250 |
| | M4 | 1000 |
| | M5 | 1000 |
| | Total Demand | 5000 |

**Table 3**

Cost and on-time fulfillment index.

| Product (P1) | Supplier | Cost (INR per unit) | On-time fulfillment index |
|--------------|----------|---------------------|--------------------------|
| Thermometer | S1 | 40 | 100 | 1 |
| | S2 | 55 | 95 | 0.95 |
| | S3 | 70 | 80 | 0.8 |
| | S4 | 100 | 50 | 0.5 |

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empirical illustration of emergency order allocation by a multi-brand distributor in an Indian case context. ABC Pharma\textsuperscript{4} is a multi-brand distributor of medical supplies and HCEs to medical stores in the Northern States of India. In the aftermath of the oxygen scarcity panic, ABC Pharma received a sudden surge in demand for HCEs from its regular buyers (medical stores). The problems encountered by ABC Pharma were manifold; they included the continuous supply of HCEs and ensuring a percentage of the supply from reliable, popular brands along with procuring from new suppliers to maintain their availability.

4.1. Input data

We used the daily demand data of HCEs, namely, electronic thermometers, pulse oximeters, oxygen concentrators, and temperature guns generated at the medical stores and received by ABC Pharma during the second wave of COVID-19, i.e. April-May 2021, in India. The demand pattern of the HCEs is presented in Table 4. The data on the supplier’s fulfillment index $SI_{ij}$ obtained for ABC Pharma is shown in Table A (see Appendix A). The estimated availability index based on the proposed strategy is shown in Tables B1-B4 (see Appendix B).

4.2. Results and discussion

The results obtained using the proposed strategy are provided in Table 5, Table 6, and Fig. 2. The average total purchase cost of each HCE against the on-time availability index $AI_j$ of an HCE is shown in Table 5. Note that the maximum on-time availability index for thermometers that can be achieved is 0.99 (99 %), for the temperature gun and pulse oximeter it is 0.97 (97 %), and for oxygen concentrator it is 0.98 (98 %).

Table 4

| Demand pattern of HCEs. |
|-------------------------|
| Daily total demand from all stores in a State of the Northern region | Mean (units) | Standard deviation (units/day) |
| Thermometer (P1) | 3709 | 803 |
| Temperature gun (P2) | 840 | 334 |
| Pulse Oximeter (P3) | 2648 | 452 |
| Oxygen Concentrator (P4) | 635 | 286 |

Table 5

| Average total purchase cost for specific availability index. |
|-------------------------------------------------------------|
| HCE | $0.99$ | $0.98$ | $0.97$ | $0.96$ | $0.95$ | $0.94$ | $0.93$ | $0.92$ | $0.91$ |
| Thermometer (P1) | 217,455 | 212,018 | 207,439 | 202,201 | 198,515 | 197,044 | 196,235 | 196,759 | 197,959 |
| Temperature gun (P2) | 53,990 | 49,879 | 47,221 | 44,956 | 42,988 | 41,367 | 40,008 |
| Pulse Oximeter (P3) | 151,025 | 146,545 | 144,225 | 145,162 | 147,022 | 149,045 | 151,025 |
| Oxygen Concentrator (P4) | 41,367 | 40,697 | 40,083 | 40,003 | 40,003 | 40,003 | 40,003 |

Note: 1. A blank cell means that no allocation of orders could be performed at that availability index. For example, product P3 has a maximum (minimum) availability index of 0.97 (0.91), respectively.
2. The shaded block represents the minimum purchase cost of product $j$ with respect to $AI_j$.

Table 6

| Minimum and maximum total purchase cost during April-May 2021 (randomly picked). |
|---------------------------------|
| Day | Min Cost (00) | Max Cost (00) | 1 % increase | Day | Min Cost (00) | Max Cost (00) | 1 % increase |
| 1 | 131,268 | 147,460 | 4048 | 12 | 87,651 | 97,673 | 2505 |
| 2 | 135,250 | 152,224 | 4244 | 13 | 96,605 | 107,874 | 2817 |
| 3 | 98,342 | 108,818 | 2619 | 14 | 99,479 | 109,602 | 2531 |
| 4 | 109,435 | 121,552 | 3029 | 15 | 105,899 | 117,793 | 2973 |
| 5 | 85,660 | 96,584 | 2731 | 16 | 136,605 | 151,456 | 3713 |
| 6 | 83,646 | 93,212 | 2992 | 17 | 104,230 | 116,869 | 3160 |
| 7 | 82,770 | 91,145 | 2094 | 18 | 86,503 | 95,669 | 2292 |
| 8 | 101,597 | 111,344 | 2437 | 19 | 120,560 | 132,781 | 3055 |
| 9 | 102,891 | 113,521 | 2658 | 20 | 98,225 | 107,293 | 2267 |
| 10 | 108,321 | 119,097 | 2694 | 21 | 104,641 | 119,546 | 3726 |
| 11 | 123,187 | 135,580 | 3098 | | | | |

Note: 1. The column “1% increase” denotes the increase in the purchase cost of an HCE if the availability index is increased by 1%.
2. The “min cost” column represents the total purchase cost at an average minimum availability index of 0.94 (Thermometer at 0.93, Temperature gun at 0.91, Pulse Oximeter at 0.95, Oxygen Concentrator at 0.96).
3. The “max cost” column represents the total purchase cost at an average maximum availability index of 0.98 (Thermometer at 0.99, Temperature gun at 0.97, Pulse Oximeter at 0.97, Oxygen Concentrator at 0.98).

\[4\] The identity of the distributor is kept confidential due to mutual agreement for information provision between distributor and the authors.

Fig. 2. Total purchase cost for 94%, 95%, and 98\% availability index of HCEs at ABC Pharma.

Further, the overall on-time availability of pulse oximeter and oxygen concentrator is higher since their minimum on-time availability index is 0.94 (94 %) and 0.95 (95 %), respectively. Table 6 shows the average...
maximum and minimum total purchase costs of the HCEs. The minimum and maximum total purchase costs are at the $AI_j$ value of 0.94 (94 %) and 0.98 (98 %), respectively. If the on-time availability index is increased by 1 % (from 0.94 to 0.95) in the HCEs, ABC Pharma has to increase INR 2909 in the daily total purchase cost during the peak due to ecosystem limitations. Fig. 2 shows the daily variation in the average total purchase costs of HCEs at $AI_j$ values of 94 %, 95 %, and 98 %.

Fig. 3. Thermometers (a) $AI$ vs average total purchase cost (b) $AI$ vs average total profit.

Fig. 4. Percentage change in average total profit and total purchase cost against $AI$ for Thermometers.

Fig. 5. Temperature guns (a) $AI$ vs average total purchase cost (b) $AI$ vs average total profit.

Fig. 6. Percentage change in average total profit and total purchase cost against $AI$ for Temperature gun.
The profile of the average total purchase cost and average total profit for an HCE product with respect to AI is presented in Figs. 3, 5, 7, and 9.

Similarly, the percentage change in the total purchase cost and total profit of each product against an availability index AI is shown in Figs. 4, 6, 8, and 10.

4.2.1. Electronic thermometers (Product 1)

Table 5 suggests that to achieve the availability of electronic thermometers by up to 99% at ABC Pharma, the total purchase cost would increase by 8.97%. If the firm wants to achieve a higher availability level with minimum purchase cost, then 93% is the on-time availability level of the thermometers. The achievement of higher on-time availability and lower total purchase cost validates the proposed strategy.

4.2.2. Temperature guns (Product 2)

As the unavailability of a temperature gun hurts the preventive care measures for controlling COVID-19, the achievement of a maximum level of 97% on-time availability index of temperature guns at ABC Pharma is a matter of great concern. Table 5 shows a huge difference in the total purchase cost at the maximum and minimum levels of the on-time availability of temperature guns. For example, to ensure a 97% on-time availability index from the level of 91%, ABC Pharma would incur an additional 25.9% increase in the total purchase cost. Fig. 5 shows that to ensure a 97% on-time availability of temperature guns, ABC Pharma incurred a 2.5% drop in its profit. Hence, ABC Pharma must have incurred losses to fulfill its pharmacy partners’ demand with maximum availability continuously. The financial records of ABC...
Our study establishes a research framework that highlights the importance of an emergency order allocation mechanism for e-medical supplies during a highly disruptive event like COVID-19. The proposed emergency order allocation mechanism characterizes the importance of e-medical supplies availability and a supplier’s on-time fulfillment index.

4.2.4. Oxygen concentrators (Product 4)

The highest on-time availability of oxygen concentrators is 98%; this may be acceptable during an emergency. The increment of 3.30% in the total purchase cost from the on-time availability level of 95% helps in achieving the 98% on-time availability of oxygen concentrators. Hence, maintaining higher levels of oxygen concentrators can be achieved without any loss to ABC Pharma.

Based on the percentage change in the total purchase cost with respect to the on-time availability index of the HCEs, the temperature guns have a higher influence on cost in comparison to the thermometers, pulse oximeters, and oxygen concentrators. Therefore, the multi-brand HCE distributor can allocate orders to suppliers based on a trade-off between the purchase cost, profit, and availability index to ensure the timely fulfillment of demand surges during a pandemic.

We have carried out a comprehensive analysis of the studies given in Table 7. The analysis has been carried out during a pandemic and focuses mainly on the allocation of medical essentials, vaccines, etc. However, an algorithm such as the one presented in our study could not be found.

5. Implications of the study

5.1. Managerial contributions

This study establishes a research framework that highlights the importance of an emergency order allocation mechanism for e-medical supplies during a highly disruptive event like COVID-19. The proposed emergency order allocation mechanism characterizes the importance of e-medical supplies availability and a supplier’s on-time fulfillment index.
in allocating orders of emergency products by a distributor to its suppliers during an extraordinary circumstance. Therein, the distributor can make a trade-off between ensuring demand fulfillment of pharmacies and profits.

Also, this study informs how the proposed order allocation strategy can assist in solving the complex issue of maintaining a higher availability of HCEs to distributors during an unprecedented situation. Since the availability of HCEs at the distributor end ensures availability at the pharmacies, our proposed algorithm is a direct intervention to ensure higher availability of HCEs in pharmacies. Furthermore, our analysis shows the financial viability of all HCEs, demonstrating the feasibility of implementing the proposed algorithm for pandemics like COVID-19.

Further, we provide the policy implications to govern a firm’s implementation of the proposed strategy in actual emergency operations.

5.2. Policy implications

- **The distributor should ensure the availability of HCEs at medical stores to maximize its social contribution.** The outbreak of COVID-19 showed a rapid increase in infections during its first, second, and third waves, respectively. Especially during the second wave, the sudden surge in infections and scarcity of HCEs weakened the fight against COVID-19 in developing economies such as India and South Africa. The distributor, a key stakeholder in ensuring the availability of HCEs, can effectively maintain a higher availability using the algorithm.

- **The proposed algorithm’s role in the enhancement of buyer–supplier interplay for a future pandemic crisis like COVID-19.** The algorithm considers the flexibility of order allocation and supplying capacity to distributors and suppliers, respectively. This unique feature in association with dynamic pricing (Section 3) provides independence to decision-makers and enhances the relationship between distributors and suppliers.

- **Application in public health centers.** The proposed mechanism can also support policymakers such as the Ministry of Health and Family Welfare (MoHFW) in ensuring a higher availability of HCEs in public distribution centers during a pandemic. Also, policymakers in public health can quickly implement the proposed mechanism to ensure higher availability of medical products and medical essentials at emergency hospitals, quarantine centers etc.

6. Conclusion

6.1. Concluding remarks

Motivated by the challenges posed by the mysterious nature of COVID-19, this study has presented a strategy to address the emergency order allocation issues to ensure the sufficient and timely availability of e-medical supplies for HCEs at pharmacies. The current work contributes to the area of emergency operations management by conceptually modelling the effect of an emergency order allocation mechanism on the on-time availability of HCEs.

The rapid spread of COVID-19, especially during the second COVID wave, created a high amount of panic and disrupted the supply chain of medical supplies globally. The impact of a disrupted supply chain on the on-time availability of HCEs is considered unfavorable in preventing the community spread of COVID-19. Therefore, this study has been conducted to ensure higher on-time availability of HCEs in the market to contain loss of life in the future; this could not be minimized due to uneven distribution of HCEs during the second COVID wave in India. Further, through an actual case example, our research has provided several findings to address the issues raised in Section 1.

Firstly, our analysis can help a multi-brand HCEs distributor to ensure the on-time availability of HCEs in the market. Specifically, the proposed strategy suggests allocating orders to qualified suppliers of HCEs based on a supplier’s on-time fulfillment index, product availability index, and cost of purchase. Secondly, the result based on an actual demand dataset of HCEs in an Indian market suggests that a minimum and maximum average of 94 % and 98 % availability of HCEs at stores could be achieved using the proposed strategy, respectively. Hence, the proposed mechanism can assist the distributor in emergency order allocation to ensure timely fulfillment of market demand. Thirdly, policymakers can use the proposed approach to design an emergency distribution mechanism for HCEs at public distribution centers, emergency hospitals, and quarantine centers across the country in the future.

6.2. Limitations and future research

Several research limitations are recognized. Firstly, being an approximate strategy, the proposed approach is only applicable for short-term supply-distribution disruptions due to pandemics like COVID-19. In particular, the issues of long supply shortages and demand surges in relation to COVID-19 and other potential pandemics can be further considered for model extension. Secondly, the current scope of this research may study COVID-19-induced supply-distribution disruptions. In reality, disruptions due to other disaster-based emergencies can be considered to generalize the applicability of the proposed model. Thus, further research is warranted. A study on the allocation of self-care essential items such as face masks, hand sanitizer, and face shields can also be made in future research. Additionally, the order allocation problem for HCEs is a dynamic multi-criteria-driven problem; therefore, in future studies, researchers can conduct a study based on those criteria and propose a guiding framework for emergency operations.

CRediT authorship contribution statement

Sachin Kumar Mangla: Writing – review & editing, Project administration, Software. Ankur Chauhan: Writing – original draft, Methodology, Conceptualization. Tannoy Kundu: Visualization, Formal analysis, Data curation. Abbas Mardani: Visualization, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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None.

Appendix A. Supplier’s fulfillment index of the study case

See Table A1.
Appendix B. Availability index $A_{ij}$ of HCEs obtained from emergency order allocation mechanism

See Tables B1-B4.

Table B1
Availability index of thermometer.

| % of total order quantity allocated to supplier | Availability Index $A_{i}$ |
|---|---|
| $S_1$ | $S_2$ | $S_3$ | $S_4$ | $A_{i}$ |
| 0.55 | 0.2 | 0.15 | 0.1 | 0.91 |
| 0.58 | 0.19 | 0.14 | 0.09 | 0.918 |
| 0.61 | 0.18 | 0.13 | 0.08 | 0.925 |
| 0.64 | 0.17 | 0.12 | 0.07 | 0.933 |
| 0.67 | 0.16 | 0.11 | 0.06 | 0.94 |
| 0.7 | 0.15 | 0.1 | 0.05 | 0.948 |
| 0.73 | 0.14 | 0.09 | 0.04 | 0.955 |
| 0.76 | 0.13 | 0.08 | 0.03 | 0.963 |
| 0.79 | 0.12 | 0.07 | 0.02 | 0.97 |
| 0.82 | 0.11 | 0.06 | 0.01 | 0.978 |
| 0.85 | 0.1 | 0.05 | 0 | 0.985 |

Table B2
Availability index of temperature gun.

| % of total order quantity allocated to supplier | Availability Index $A_{i}$ |
|---|---|
| $S_5$ | $S_6$ | $S_7$ | $A_{i}$ |
| 0.75 | 0.15 | 0.1 | 0.913 |
| 0.77 | 0.14 | 0.09 | 0.919 |
| 0.79 | 0.13 | 0.08 | 0.925 |
| 0.81 | 0.12 | 0.07 | 0.931 |
| 0.83 | 0.11 | 0.06 | 0.937 |
| 0.85 | 0.1 | 0.05 | 0.943 |
| 0.87 | 0.09 | 0.04 | 0.949 |
| 0.89 | 0.08 | 0.03 | 0.955 |
| 0.91 | 0.07 | 0.02 | 0.961 |
| 0.93 | 0.06 | 0.01 | 0.967 |
| 0.95 | 0.05 | 0 | 0.974 |

Table B3
Availability index of pulse oximeter.

| % of total order quantity allocated to supplier | Availability Index $A_{i}$ |
|---|---|
| $S_5$ | $S_6$ | $S_7$ | $S_8$ | $A_{i}$ |
| 0.55 | 0.2 | 0.15 | 0.1 | 0.937 |
| 0.58 | 0.19 | 0.14 | 0.09 | 0.94 |
| 0.61 | 0.18 | 0.13 | 0.08 | 0.943 |
| 0.64 | 0.17 | 0.12 | 0.07 | 0.947 |
| 0.67 | 0.16 | 0.11 | 0.06 | 0.95 |
| 0.7 | 0.15 | 0.1 | 0.05 | 0.954 |
| 0.73 | 0.14 | 0.09 | 0.04 | 0.957 |
| 0.76 | 0.13 | 0.08 | 0.03 | 0.96 |
| 0.79 | 0.12 | 0.07 | 0.02 | 0.964 |
| 0.82 | 0.11 | 0.06 | 0.01 | 0.967 |
| 0.85 | 0.1 | 0.05 | 0 | 0.971 |
Table B4

| % of total order quantity allocated to supplier | Availability Index |
|-----------------------------------------------|--------------------|
| S3                                            | S4                 | S8                 | AI     |
| 0.1                                           | 0.15               | 0.75               | 0.95   |
| 0.09                                          | 0.14               | 0.77               | 0.93   |
| 0.08                                          | 0.13               | 0.79               | 0.95   |
| 0.07                                          | 0.12               | 0.81               | 0.96   |
| 0.06                                          | 0.11               | 0.83               | 0.96   |
| 0.05                                          | 0.1                | 0.85               | 0.96   |
| 0.04                                          | 0.09               | 0.87               | 0.96   |
| 0.03                                          | 0.08               | 0.89               | 0.96   |
| 0.02                                          | 0.07               | 0.91               | 0.97   |
| 0.01                                          | 0.06               | 0.93               | 0.97   |
| 0     | 0.05               | 0.95               | 0.97   |

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