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ORIGINAL RESEARCH

Reconfiguration of food grain supply network amidst COVID-19 outbreak: an emerging economy perspective

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Abstract

The procurement of food grains from farmers is one of the biggest challenges under the COVID-19 outbreak due to country-wise lockdowns. The present study aims to reconfigure the existing food grain supply chain network. The study advances the extant literature by proposing a novel mathematical model that considers the government guidelines issued to procure food grains from farmers under the COVID-19 situation. The model includes personal distancing, a key parameter relevant in the COVID-19 crisis, and has remained unaddressed in the existing literature. The proposed model is tested in India. The effect of different parameters like personal distancing cost, carbon emission cost, fixed cost, and transportation cost is also investigated under a given set of procurement centers. Finally, the procurement schedule for each procurement center is generated, which is especially useful for managing its activities and is also helpful to farmers to streamline the process. Results indicate that the proposed model is highly effective under pandemic emergencies like the current COVID-19 crisis. Policymakers and the government will find this model helpful in drafting relevant policies regarding food grain procurement under emergencies such as the COVID-19 outbreak. The distribution segment of the supply chain network is not part of the present research work. In future studies, this part could be then added to the whole of the procurement process, and both procurement and distribution can be assessed together again.

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Keywords Food grain procurement · Supply chain management · Supply chain reconfiguration · COVID-19

1 Introduction

COVID-19 is one of the most significant pandemic challenges that the world has seen over the last few decades. The impact of the crisis is so immense that as of 2 May 2020, there were 2,078,596 active cases across the world with 239,622 deaths. India is no different and has seen 26,046 active COVID-19 cases and 1226 deaths (World Health Organization). To mitigate the effects of the COVID-19 crisis, various countries announced lockdowns with duration ranging from a few weeks to months. Before the announcements, these countries had already taken several measures such as travel restrictions, closing educational establishments and health clubs, banning mass gatherings, and encouraging enterprises to promote work from home (Aytekin, 2020). Amid the crisis, though the lockdowns proved to be an effective measure in containing the number of cases, some immediate challenges arose from the disruption of economic activities. One of the most critical challenges is the disruption in the supply chain of food grains. Thi supply chain comprises farmers, procurement centers, warehouses, logistics, retailers, and end customers, as shown in Fig. 1. COVID-19 has disrupted the procurement of food grains due to nationwide lockdown in India, leading to significant food grain losses. A survey of Indian farmers across nine states during the lockdown found that about 29 percent of the farmers were holding their harvests. About 13 percent of them had to sell their produce

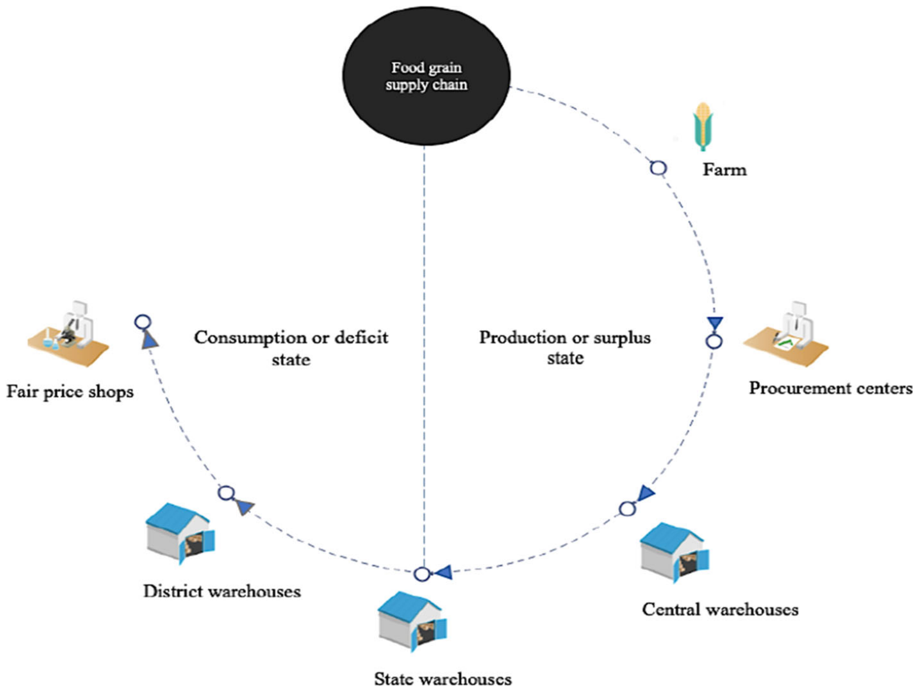

Fig. 1 A typical food grain supply chain network in India

at throwaway prices, and about seven percent of farmers stated that their produce was wasted its entirety (IFPRI, 2020).

Food grain losses are mainly attributed to improper planning, poor infrastructure, and inefficient resource utilization (Parfitt et al., 2010). It is essential to procure food grains from the farmers after the harvest season to maintain the supply chain and prevent losses due to a lack of storage space for the harvested food grains. Sustaining the supply chain of food grains is even more critical to emerging economies such as India, with a large population and high poverty rate, for the millions of people dependent on PDS (public distribution system) and the farmers to receive fair prices for their harvest (FCI, 2020). It is to be noted that there cannot be haphazard procurement of food grains during the ongoing pandemic emergency. Hence the procurement process should adhere to the personal distancing norms, i.e., each day, only limited numbers of farmers will be allowed to bring their produce to procurement centers. The distance between the villages where the farmers live and the procurement centers should be within the recommended distance so that farmers do not have to travel long distances and can primarily stay in their homes to prevent the transmission of COVID-19. These constraints call for an increase in procurement to help ensure the farmers' health and welfare. The introduction of these constraints is mandatory to safeguard and fine-tune further the supply chain of food grains during pandemic emergencies and reconfigure the supply chain network of food grains. Against this background, the study answers the following research question: *How to reconfigure the food grain supply network under the pandemic crisis?*

Given the above question, the present study was planned to reconfigure the existing food grain supply chain network by formulating a mixed-integer programming model (MILP) incorporating the government guidelines issued to procure food grains from farmers. In this model, we introduced new constraints such as personal distancing, which is highly relevant to the COVID-19 crisis and has not been addressed in the extant literature. The study analyzed the data available from one wheat producer in India using the proposed MILP model, which minimizes the procurement center's fixed costs and variable transportation costs, emission costs under unique constraints such as personal distancing and farmers' movement restricted within the recommended distance from their villages. A sensitivity analysis is also conducted to provide valuable insights to policymakers for effective decision-making about the supply chain of food grains under pandemic emergencies like COVID-19.

The remainder of the paper is structured as follows. Section 2 deliberates relevant literature on the supply chain network for procurement of food grains, its challenges, and the modeling approach, Sect. 3 explains the problem and conceptual framework. Section 4 describes the proposed mixed-integer programming model formulation for the supply chain network to procure food grains under the COVID-19 outbreak. Section 5 presents the application of the proposed model with the help of a case study, along with the insights evolved from the results. Section 6 presents the results and their discussion. Finally, Sect. 7 concludes the manuscript with unique contributions, managerial implications, theoretical implications, public policy implications, and limitations and future research directions of the present study.

2 Literature review

During the COVID-19 pandemic, all food supply chains were severely impacted, including fresh vegetables, fruits, bakery items, perishable goods, and, finally, food grains (Ivanov & Dolgui, 2020; Scheibe & Blackhurst, 2018). Food scarcity is unavoidable in such a tight lockdown, which interrupted most logistics activities. Food scarcity during COVID-19 is considered as a national disaster. People have been stopped from purchasing food grain due to the risk of infection (Narayanan et al., 2020). To overcome the chance of community infection disaster, disaster management techniques typically utilized have a series of steps: establishing communication infrastructure and performing relief operations (Takagi & Bricker, 2015). Disaster networks can be classified as disaster mitigation networks and disaster relief networks. Various organizations initiated to strengthen disaster management systems by applying practices and experiences to respond to COVID-19 and modify their approaches to responding to disasters under the COVID-19 pandemic (Ishiwatari et al., 2020).

Response operations should cover other needs of the affected people and the long-term needs of the wider population. Djlante et al. (2020) proposed measures to strengthen responses to the COVID-19 pandemic by providing scientific knowledge in understanding risks, strengthening risk governance, and enhancing community-based activities. One of the most critical tasks of disaster management is to control the spread of COVID-19. The spread of COVID 19 can be minimized by reconfiguring the supply chain network for purchasing the food grain that is also affected by the pandemic like COVID 19. The supply chain network for the procurement of food grains should be reconfigured to mitigate the spread of COVID 19. The spread of COVID 19 due to the supply chain network for the procurement of food grains can be mitigated as follows: (i) the long travel of the farmers from their villages to the procurement center should be restricted by opening the procurement centers in nearby areas, (ii) the crowd in the procurement center may be restricted by allowing the limited number of farmers in the procurement center, (iii) the IT-enabled supply chain network can be used for the purchasing of the food grains. In a study of disaster relief operations, it is reported that there are multiple challenges during disaster relief operations like needs assessment, procurement, warehousing, transportation and distribution, and IT. These factors have not been extensively studied in the literature; given their growing influence during disaster relief operations, they require more attention from researchers (Maghsoudi & Moshtari, 2021). Further, the problem becomes more complex if disaster relief operations respond to COVID-19.

2.1 Role of procurement in food grain supply chain network

Procurement and distribution are two critical functions of the food grain supply chain network, as shown in Fig. 1. The food grain supply chain network can be broken into two parts, i.e., surplus and deficit conditions. In the ***surplus state*** of the food grain supply chain network, farmers bring their harvest to the ***procurement centers***, and these centers ship the harvest to the ***central warehouses*** of the surplus state. In the ***deficit section*** of the supply chain network, the food grains are shipped from the ***surplus state's central warehouses*** to the ***deficit state's state warehouses*** and then shipped to ***district warehouses***. The food grains finally reach ***fair price shops***. In developing countries such as India, the food grain supply chain network is very complex. In particular, researchers have paid little attention to the procurement process in a complex network (Mogale et al., 2018). The reported literature on the supply chain network for procurement of food grains is segregated into three major categories: facility location and allocation problems, the role of procurement chain, and modeling of the supply chain network.

In developing countries, the food grain supply chain network is inefficient due to inadequate infrastructure, excessive complexity, ineffective traditional procurement systems, and low usage of information technology in the supply chain network (De Boer et al., 2002; Sazzad, 2014). There are several challenges in the food grain supply chain network due to unequal supply and demand (Sahle et al., 2018). The food grain supply chain infrastructure is inefficient to accommodate the dynamic market requirement (Du et al., 2009). Additionally, lack of planning, inappropriate management practices, inefficient procurement system, poor storage, and irregular vehicles are the main factors for post-harvest losses (Shukla & Jharkharia, 2013). The post-harvest losses are significant due to ineffective policies and resource utilization (Parfitt et al., 2010). Several researchers pointed out gaps in the food grain supply chain, like unscientific procurement processes, inadequate storage facilities, improper planning coordination decisions, leakage, and irregular distribution of food grains (Balaji et al., 2016; Maiyar & Thakkar, 2020; Sazzad, 2014; Singha Mahapatra & Mahanty, 2018). National Commission on farmers in India (2004) argued that every village should have at least one procurement center within a 5 km radius; however, most farmers have to travel approximately 30 km to reach the nearest procurement center. This leads to an increase in transportation costs, travel time, and carbon emissions.

Furthermore, Gorton et al. (2006) pointed out that misinformation between farmers and processors leads to a mismatch between demand and supply. According to Hill (2008), processed food and fresh produce are transported approximately 1300 and 1500 miles in the USA, respectively. The longer distance leads to higher fuel consumption, carbon emissions, pollution, environmental degradation, and global warming (Rajkumar, 2010). Collaboration between producers and cooperatives helps in reducing such losses (Despoudi et al., 2018; Ghadge et al., 2017). The complexity of the food grain supply chain network is further increased by the simultaneous consideration of food quality and sustainability (Van Der Vorst et al., 2009).

2.2 Facility location allocation problem

Over the last few decades, there is a growing focus on the production and procurement of food grain procurement literature. Very specifically, Mogale et al. (2018) developed a multi-objective, multi-modal, and multi-period mathematical model for the grain silo location-allocation problem. The model minimizes total supply chain network cost and total lead time simultaneously, using a multi-objective algorithm. Gholamian and Taghanzadeh (2017) developed an integrated supply chain of wheat products that can be used to select suppliers and determine the amount of wheat to import, the distribution of grain, and the production of certain wheat by-products. They incorporated variables such as different types of grain and modes of transportation and the import and export of grain.

Further, Nourbakhsh et al. (2016) reported a mathematical model for minimizing infrastructure investment and the monetary value of post-harvest losses. They considered the number and location of drying facilities, transportation routing, and transhipments between roadways and railways as decision variables in their model. The model was tested using a case study of the state of Illinois. The food's quality was incorporated into the multi-period production and distribution planning problem of a two-stage network (Rong et al., 2011). They developed the MILP model, which minimizes the total costs—including production, transportation, inventory, and waste disposal—along with the cooling cost of transportation equipment and storage facilities. Ge et al. (2015) used a simulation model to minimize the handling cost of the wheat supply chain in the Canadian grain industry. The main objective of their study was to find the most effective quality testing strategies to mitigate contamination risks under the new trust-based declaration system of wheat segregation.

Besides, Khamjan et al. (2013) developed a mathematical model that was solved using a heuristic to decide the location of a sugarcane loading station in Thailand. The main objective of their model was to minimize the facility location cost, traffic congestion cost, and transportation cost. Jouzdani et al. (2013) developed a mathematical model to study the dynamic dairy facility location and supply chain planning problem with traffic congestion and uncertain demand by using the real-world case study of Tehran. The main objective of their model was to minimize the facility location cost, traffic congestion cost, and raw/processed milk and dairy products transportation cost. Eskigun et al. (2005) addressed an outbound supply chain network design problem by considering the transit time, location of distribution centers, and transportation mode. The objective function was formulated based on transportation and lead time cost. Hyland et al. (2016) compared the conventional transportation service with country elevators against a shuttle service with terminal elevators using a mathematical model of grain transportation. Rancourt et al. (2015) reported three location models for designing last-mile food aid distribution networks with the objective functions of minimizing social welfare cost, maximizing need coverage, and minimizing the required number of distribution centers. Kchaou Boujelben et al. (2016) presented the MILP model for the multi-period facility location problem using several constraints. They used a dynamic clustering method to determine transportation routes from distribution center customers as the input parameter.

2.3 Modelling of supply chain network for the procurement of food grains

The complexity of the food grain supply chain network has prompted researchers to study it from different perspectives during the last decade (Ahumada & Villalobos, 2009; Akkerman et al., 2010; Amorim et al., 2016; Brandenburg et al., 2014; Esteso et al., 2018; Soysal et al., 2014). Most of the reported research on the modeling of food grain supply chain networks is generic, and hence, there is a need to develop specific food grain supply chain networks. Table 1 summarizes the modelling approaches used in designing the food grain supply chain network to identify researchers willing to work further in the area quickly. In most of the reported literature on modelling the food grain supply chain, the MILP approach considering fixed facility cost and variable transportation cost was used (Khamjan et al., 2013; Mohammadkhanloo, 2013; Neungmatcha et al., 2013; Nourbakhsh et al., 2016). Clustering is a process of partitioning data into clusters. Several clustering algorithms, such as k-means clustering, which is an algorithm for partitioning data into k distinct clusters, fuzzy c means, and center of gravity, used by researchers to decide the location of procurement centers in the context of food grain supply chain networks (Bosona & Gebresenbet, 2011; Pathumnakul et al., 2012; Sutanto et al., 2018; Zamar et al., 2017). Govindan et al. (2014) and Saranwong and Likasiri (2017) considered the simultaneous use of location and transportation decisions in their studies of the food grain supply chain network. Additionally, the location analysis was supported by GIS (Geographic Information System). A comparison of the existing models on the supply chain network design for the procurement of food grains with the model developed in the present research is shown in Table 1.

3 Research issues and objectives

The above review recognizes the following research issues, prompting the research in the supply chain network to procure food grains during a pandemic crisis.

- The food supply chain network is complex in developing countries like India, as there is hardly any scientific approach followed during the procurement and distribution processes (Mogale et al., 2020).

Table 1 Comparison of the existing models for the food grain supply chain network design

Study	Objective function and constraints											Clustering			Clustering technique	Optimization approach
	Product	Objectives	Model	FFC	FTC	VTC	OC	EC	MDC	SDC	PDC	Distance	Density	ADBVP		
Bosona and Gebresenbet (2011)	Meat	Single	LP			✓						✓			GIS Software	Route Logix software
Pathumnakul et al. (2012)	Sugarcane	Single	MIP	✓		✓						✓			MFCM and COG	Heuristic
Yakovleva et al. (2012)	General	Multiple	AHP													AHP
Asgari et al. (2013)	Wheat	Single	LIP		✓	✓										Lingo and GA
Khamjan et al. (2013)	Sugar cane	Single	MIP													Heuristic
Mohammadkhanloo (2013)	General	Single	MILP	✓		✓						✓			K-MEANS with SA	G A
Govindan et al. (2014)	Food	Single	MIP	✓	✓	✓	✓									AMOVNS NSGA-IIA
Soysal et al. (2014)	Beef	Multiple	MIP		✓	✓										Epsilon constraint
Validi et al. (2014)	Dairy	Multiple	MIP	✓		✓										NSGA-II and MOGA-II
Maiyar et al. (2015)	Grain	Single	MINLP			✓										SLPSO and PSOCP
Nourbakhsh et al. (2016)	Grain	Single	MIP	✓		✓	✓									MIP
Amorim et al. (2016)	Processed food	Multiple	MILP			✓										MILP
Zamar et al. (2017)	Bale	Single	MINLP			✓						✓			K means	Heuristic

Table 1 (continued)

Study	Objective function and constraints											Clustering			Clustering technique	Optimization approach
	Product	Objectives	Model	FFC	FTC	VTC	OC	EC	MDC	SDC	PDC	Distance	Density	ADBVP		
Mohammed and Wang (2017)	Meat	Multiple	MILP			✓	✓									LP metrics
Mogale et al. (2017)	Wheat	Single	MINLP		✓	✓										Tabu search
Saranwong and Likasiri (2017)	Sugarcane	Single	MIP	✓		✓										Cplex and Heuristic
Sutanto et al. (2018)	General	Single	MIP			✓						✓			K means	
Allaoui et al. (2018)	General	Multiple	MILP	✓		✓										MCDM + CPLEX
Mogale et al. (2020)	Grain	Single	MILP	✓	✓	✓						✓	✓		NKHGA	CPLEX
Maiyar and Thakkar (2020)	Grains	Multiple	MINLP		✓			✓								Particle swarm optimisation
Our model	Wheat	Single	MILP	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	K-means with IP	CPLEX MILP

FFC fixed facility cost, *FTC* fixed transportation cost, *VTC* variable transportation cost, *OC* operational cost, *EC* carbon emission cost, *MDC* max distance criteria, *SDC* personal distancing cost, *PDC* personal distancing constraint, *ADBVP* allowable distance between village and procurement center. *IP* integer programming, *LP* linear programming, *MILP* mixed linear integer programming, *MINLP* mixed-integer nonlinear programming

- The existing supply chain networks for the procurement of food grains do not consider the personal distancing constraints in the procurement centers, which is highly relevant during pandemic emergencies like the COVID-19 outbreak.
- None of the existing supply chain networks for the procurement of food grains provides a facility for farmers to sell their produce within the recommended distance from their villages. This is another relevant constraint under lockdown conditions due to the COVID-19 outbreak.
- There is scant research related to food grain transportation and distribution in the context of supply chain management (Asgari et al., 2013; Maiyar et al., 2015)
- Optimization of transit time to reduce post-harvest losses is not considered in the reported literature.

Taking cues from the critical research issues identified in the literature review, the present study aims at addressing the following:

- A food grain supply chain network will be modified so that both the personal distancing constraints and farmers' movements are restricted within the recommended distance from villages for selling food grains during a pandemic crisis like the COVID-19 outbreak. The modified supply chain network will minimize the fixed procurement center's cost, transportation cost, operational cost, carbon emission cost, and personal distancing cost.
- The two-stage methodology based on k-means clustering with integer programming and MILP is used to design the supply chain network to procure food grains from the farmers.
- A sensitivity analysis is performed for analyzing the effects of different parameters, like the number of procurement centers, procurement cycle time, emission cost, and transportation cost, on the designed supply chain network under a given scenario.
- A case study of the North India district is used to demonstrate the steps of a mathematical model based on k-means clustering with integer programming and MILP approaches.
- The schedule for each procurement center is developed to inform farmers in advance through mobile messaging the time and day for selling their produce. This will prevent overcrowding in the procurement center and will ensure compliance with personal distancing criteria. This information technology-enabled supply chain network will help in the procurement of food grains.

A summary of comparative analysis of the existing models on the supply chain network design for the procurement of food grains with the model developed in the present research is presented in the table above. This comparison is made regarding objective functions, constraints, variables, clustering approaches used in designing the food grain supply chain network. This comparative analysis of the existing literature is very useful for the researchers willing to work further in the area. The comparative analysis of the current food grain supply chain models indicates that none of the reported models on food grain supply chain use social distancing cost (SDC), personal distancing criteria (PDC), and allowable distance between village and procurement center (ADVP). These observations are very pertinent during a pandemic crisis and warranted further research in the area. Hence, there is a need to reconfigure the existing food grain supply chain network by incorporating the above observations.

4 Problem description and conceptual framework

Wheat is the most cultivated crop in the world, feeding approximately 4.5 billion people daily. It is a staple food for developing and developed countries and a rich source of multiple essential nutrients, such as protein, dietary fiber, manganese, phosphorus, and niacin. The demand for wheat is on the rise due to the increasing population and the reasonably consistent nutritional habits of people worldwide. The onus of ensuring food security is on wheat as it feeds most of the world's population. Russia, U.S.A., and Canada are the world's major wheat exporters, while developing countries are the major importers (transferring food grains from surplus nations to deficit nations). The process involves stocking food grains and then exporting them to deficit nations.

Given the above, procurement and storage are the two most vital elements of the supply chain network of food grains. Due to the worldwide lockdown during the COVID-19 pandemic, there has been a disruption in the supply chain network that hinders food grains' procurement. Hence, there is an urgent need to restore the supply chain network to procure the food grain in a dynamic environment.

The governments in many emerging economies have recently introduced guidelines to reduce congestion and ensure personal distancing in procurement centers (yards) amid the rising number of cases of COVID-19, which is considered a worldwide disaster. Several countries have issued guidelines that allow only 100 farmers who have e-tokens (provided after registration on an online portal) to bring their produce to the procurement centers each day. The e-tokens are issued by the center in charge within 1 week and sent to the farmer through mobile messaging. The provision of registration at the purchase center is also possible through the verification of an identity card. Another set of guidelines instructs that the distance between villages and procurement centers should be within a stated distance. The farmers do not have to travel long distances and can stay in their homes to prevent the possible transmission of COVID-19.

In light of these guidelines, the existing supply chain network for the procurement of food grains was reconfigured using k-means clustering with integer programming and mixed linear integer programming approaches. Data available from a wheat-producing district in North India were analyzed using the proposed models, which minimize the fixed procurement center's cost, fixed transportation cost, variable transportation cost, carbon emission cost, and social distancing cost under unique constraints such as personal distancing and the allowed distance between village (V_i) and procurement center (PC_j). A conceptual framework for a typical supply chain network is shown in Fig. 2.

Here, PC_j is the jth procurement center, where food grain is procured from the farmers, and CW_w is the w^{th} central warehouse where food grain is stored which is transported from the procurement centers (PC_j).

In the development of the food grain supply chain model following assumptions are made, (i) the capacities of central warehouses and the availability of food grains are known with certainty, (ii) the food grain is collected at procurement centers and transported to central warehouses, (iii) the distance between the villages to the procurement centers and from procurement centers to central warehouses are known with certainty, (iv) The number of farmers allowed in the procurement center on daily basis is known with certainty, (v) the low truckload vehicles and high truckload vehicles are available without any shortage, (vi) the fixed cost for establishing a procurement center is known with certainty, (vii) the fixed cost, transportation costs, and emission cost of low truckload vehicle and high truckload vehicle are known with certainty, (viii) the capacity of low truckload and high truckload vehicles are known with certainty, (ix) the maximum distance is allowed between a village and a procurement center, (x) every farmer is allowed to sell a fixed amount of food grains.

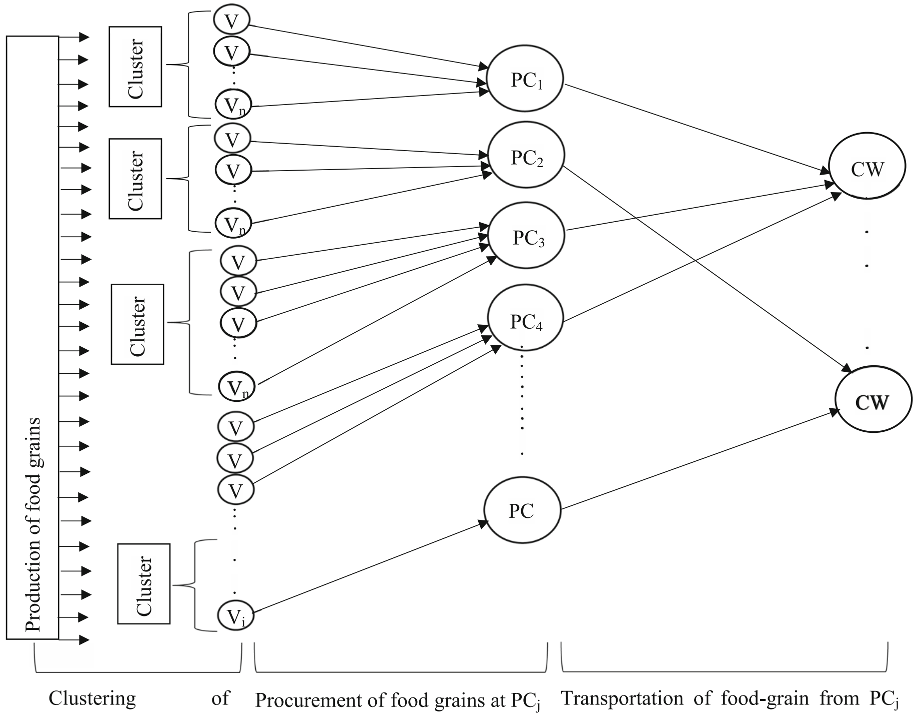

Fig. 2 Supply chain network for the procurement of food grains

5 Mathematical model formulation

5.1 Clustering of villages for identifying the location of procurement centers

K-means clustering is a method to partition *n* villages into *k* non-overlapping sub-groups (clusters) in which each village belongs to the cluster's nearest mean (cluster centroid). It is used in the present work for selecting k procurement centers in such a way that, after assigning all the villages to the nearest procurement center (cluster center), the total sum of distances between the villages and procurement centers is minimal. In this paper, a mathematical model is developed to determine the clusters of villages in such a way that the distance between villages and procurement centers are within the recommended distance so that the farmers do not have to travel long distances and can stay in their homes to prevent the possible transmission of COVID-19. This model tries to locate *p* procurement centers to minimize the total weightage transport distance between villages and procurement centers. The formulation of the mathematical model is as follows:

Notations

i: the set of villages
j: the set of procurement center locations
n = the number of villages in a cluster
d_{ij} = distance between village i and candidate procurement center j
k = max number of procurement centers that can be allowed
Wi = weight allocated to each village (food grains to be procured from village i)

Decision variables

$$X_{jj} = \begin{cases} 1, \ if \ location \ j \ is \ selected \ to \ open \ the \ procurement \ center \\ 0, \ otherwise \end{cases}$$

$$X_{ij} = \begin{cases} 1, \ if \ village \ i \ is \ allocated \ to \ central \ point \ (procurement \ center) \ j \\ 0, \ otherwise \end{cases}$$

$$\text{Min} \sum_{i} \sum_{j} wi \times d_{ij} \times X_{ij} \tag{1}$$

$$\sum_{j=1}^{n} X_{jj} = k \tag{2}$$

$$\sum_{j=1}^{n} X_{ij} = 1 \quad \forall \text{ i} \tag{3}$$

$$X_{ij} \le X_{jj} \quad \forall \text{ i, j} \tag{4}$$

The objective function is represented by Eq. 1 that minimizes the total weightage transport distance between villages and procurement centers. Constraint 1 is represented by Eq. 2, which ensures that precisely k locations are selected as procurement centers. Constraint 2 is represented by Eq. 3, which ensures that a village i can be assigned to only one location j. Constraint 3 is represented by Eq. 4, which ensures that each village is assigned to a central location (procurement center) only.

5.2 MILP model for the reconfiguration of the supply chain network for the procurement of food grains

The MILP model is developed to reconfigure the existing supply chain network for the procurement of food grains, minimize the fixed cost of procurement centers, transportation cost from villages to procurement centers, transportation cost from procurement centers to central warehouses and carbon emissions cost. Number and location of procurement centers, allocation of villages to procurement centers and procurement centers to a central warehouse, and procurement cycle time are the decision variables. These decision variables are computed by using some unique constraints like personal distancing in procurement centers and keeping distance between villages and procurement centers within the recommended distance so that the farmers do not have to travel long distances and can stay in their homes to prevent possible transmission of COVID-19. It is assumed that the capacities of central warehouses and the availability of food grains are known.

Notations:

i: villages
j: procurement centers
w: central Warehouses
LT: low truckload type vehicle
HT: full truckload type vehicle

Parameters	Descriptions
v	Number of villages
p	Number of procurement centers
w	Number of central warehouses
f_j	Fixed cost of setting up a procurement center at location j
f_{LT}	Fixed cost of a low truckload
f_{HT}	Fixed cost of a large truckload
N_{LTi}	Number of low truckloads available at village i
N_{HTj}	Number of large truckload vehicles available at procurement center j
ρ	The capacity of low truckload type vehicle
σ	The capacity of large truckload type vehicle
γ_w	The capacity of central warehouse w
β_j	The capacity of procurement center j
d_{ij}	Distance between village i to procurement center j
d_{jw}	Distance between procurement center j to central warehouse w
t_{ij}	Shipping cost per ton and KM from village i to procurement center j
t_{jw}	Shipping cost per ton and KM from procurement center j to central warehouse w
OC	Food grain handling cost per ton of food grain at procurement center
$CE^{LT}{}_{ij}$	Amount of carbon emission per unit distance for the low truckload type vehicle
$CE^{HT}{}_{jw}$	Amount of carbon emission per unit distance for the large truckload type vehicle
ϕ	Per unit cost of carbon emission
F_{ij}	Number of farmers of the village i allocated to procurement center j
S_c	Personal distancing cost
μ_s	Personal distancing coefficient
FG_i	Food grain available at village i
λ	Quantity of food grain allowed to sell by a farmerQuantity of food grain allowed to sell by a farmer
Θ	Number of farmers are allowed per day to sell their produce in a procurement center

Decision variables
$X_j = \begin{cases} 1, & \textit{if procurement center is opened at location } j \\ 0, & \textit{otherwise} \end{cases}$
$X_{ij} = \begin{cases} 1, & \textit{if village i is assigned to the procurement center } j \\ 0, & \textit{otherwise} \end{cases}$
$X_{jw} = \begin{cases} 1, & \textit{if procurement center } j \textit{ is assigned to the central warehouse } w \\ 0, & \textit{otherwise} \end{cases}$
$P_j =$ *capacity of procurement center opened at location j*
$Q_{ij} =$ *quantity of foodgrain transported from village i to procurement center j*
$Q_{jw} =$ *Quantity of foodgrain transported from procurement center j to central warehouse w*
$LT_{ij} =$ *Number of low truckload type vehicle used to transport foodgrain from village* i *to procurement center* j
$HT_{jw} =$ *Number of full truckload type vehicle used to transport foodgrain from procurement center* j *to central warehouse w*
$\psi_j =$ *Procurement cycle time for procurement center j*

Objective function: The objective function minimizes the total supply chain network cost to procure food grains. It includes the fixed cost of the procurement center, fixed and variable transportation costs from village to procurement center, fixed and variable transportation costs from procurement center to central warehouse, carbon emission cost, and personal distancing cost. The objective function Equation is represented by Eq. 5.

$$\sum_{j=1}^{p} f_j X_j + \sum_{i=1}^{v}\sum_{j=1}^{p} f_{LT} LT_{ij} + Q_{ij} d_{ij} C_{ij} + \sum_{j=1}^{p}\sum_{w=1}^{cw} f_{HT} HT_{jw} + Q_{jw} d_{jw} C_{jw} + \left(\sum_{i=1}^{v}\sum_{j=1}^{p} Q_{ij} + \sum_{i=1}^{v}\sum_{j=1}^{p} Q_{jw}\right) O_c$$
$$+ \left(\sum_{i=1}^{v}\sum_{j=1}^{p} LT_{ij} d_{ij} CE_{ij}^{LT} + \sum_{i=1}^{v}\sum_{j=1}^{p} HT_{jw} d_{jw} CE_{jw}^{HT}\right)\phi + \sum_{i=1}^{v}\sum_{j=1}^{p} F_{ij} S_c \mu_s \tag{5}$$

Constraints:

$$Q_{ij} \le X_{ij} FG_i \tag{6}$$

Constraint Eq. 6 ensures the food grains capacity restriction of village i.

$$X_{ij} \le X_j \tag{7}$$

Constraint Eq. 7 ensures that village i transport the food grains to procurement center j only if the procurement center is opened at location j.

$$\sum_{j=1}^{p} X_{ij} = 1 \quad \forall\, i \tag{8}$$

Constraint Eq. 8 ensures that each village is assigned to only one procurement center.

$$\sum_{i=1}^{v} Q_{ij} \le P_j \quad \forall\, j \tag{9}$$

The total quantity of food grains supplied to procurement center j ensures the capacity of procurement center j, as shown by Eq. 9.

$$Q_{jw} \le X_{jw} \sum_{i=1}^{v} Q_{ij} \quad \forall\, j, \forall\, w \tag{10}$$

Constraint Eq. 10 indicates that amount of food grains transported from procurement center j to central warehouse w is ensured by the amount of food grain procured at procurement center j from all assigned villages. This constraint also ensures that procurement center j can transport the food grain to central warehouse w only if procurement center j is set to central warehouse w.

$$X_{jw} \le X_j \quad \forall\, j, \forall\, w \tag{11}$$

Constraint Eq. 11 ensures that the opened procurement center j can be assigned to the central warehouse w.

$$\sum_{j=1}^{p} Q_{jw} \le \gamma_w \quad \forall\, w \tag{12}$$

Constraint Eq. 12 ensures that the amount of food grains transported from all opened procurement centers is less than or equal to the storage capacity of the central warehouse w.

$$Q_{ij} \le \rho LT_{ij} \quad \forall\, i, \forall\, j \tag{13}$$

Constraint Eq. 13 ensure the requirement of the low-capacity truck vehicle from village i to procurement center j

$$LT_{ij} \leq N_{LTi} \quad \forall\, i, \forall\, j \tag{14}$$

Constraint Eq. 14 ensures the availability of a low truckload to each village.

$$Q_{jw} \leq N_{HTj} HT_{jw} \tag{15}$$

Constraint Eq. 15 ensures the requirement of the large capacity truck vehicle from procurement center j to warehouse w.

$$HT_{jw} \leq N_{HTj} \quad \forall\, j, \forall\, w \tag{16}$$

Constraint Eq. 16 ensures the availability of a large truckload-type vehicle at each procurement center.

$$\sum_{i=1}^{v} Q_{ij} = \lambda\theta\psi_j \quad \forall\, j \tag{17}$$

Constraint Eq. 17 ensure the personal distancing constraint

$$X_j \in \{0, 1\},\ X_{ij} \in \{0, 1\},\ X_{jw} \in \{0, 1\} \tag{18}$$

Constraint Eq. 18 represents the binary variables.

$$Q_{ij},\ Q_{jw} \geq 0 \tag{19}$$

Equation 19 represents the non-negativity constraints

$$LT_{ij},\ HT_{ij} = integer \tag{20}$$

Equation 20 represents the integer constraints.

6 Case study for the procurement of food grains from a North Indian district

As the world tries to deal with the ongoing COVID-19 pandemic through a slew of measures such as lockdowns, experimental vaccines, extensive testing, and human trials, the impact is quite evident on two fronts—economic activities and human lives. India is the largest producer of rice and wheat in the world. Northern India is the largest producing region within India, so a case study of a district of North India is considered here to validate the mathematical model developed for the reconfiguration of the supply chain network. The selected district has 57 villages (refer to "Appendix A" section for tabular representation and Fig. 3 for visual representation) and 29 procurement centers (refer to "Appendix D" section). It may be noted that a large number of procurement centers results in high fixed costs. Considering this, an ideal number of centers should be decided to focus on fixed costs and personal distancing criteria. A population of 48,771 farmers and 29 procurement centers accounts for approximately 856 farmers per village and 1,682 farmers per procurement center, or two villages per procurement center and not more than 100 farmers allowed in the procurement center per day to sell their produce (*Refer to "Appendix C" section for village-wide farmer distribution*). The food grain is collected at procurement centers and transported to central warehouses (there are three central warehouses used to store the food grains collected in

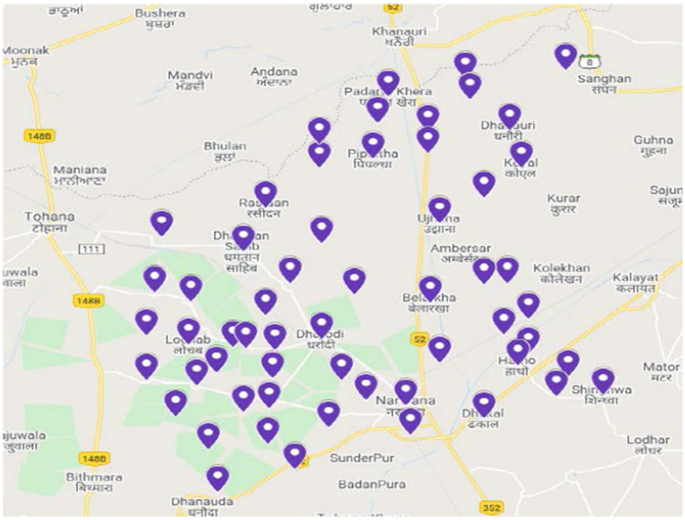

Fig. 3 Villages of a district of North India

the procurement centers). “Appendix B” section exhibits the distance matrix of procurement centers and central warehouses.

The fixed cost for establishing a procurement center is \$30,000 to \$60,000. The fixed cost of low truckload (LT) and high truckload (HT) type vehicles is \$8 to \$15 and \$20 to \$30, respectively. Transportation cost is \$0.30/ton/km for LT and HT-type vehicles. The emission cost is \$6/km for an LT-type vehicle and \$7/km for an HT-type vehicle. The maximum distance allowed between a village and a procurement center is 12.5 km. Each farmer is allowed to sell 5 tons of food grain. The number of farmers in a village available for selling their produce is 138 to 3459. The storage capacity of the central warehouse is 80,000 to 120,000 tons. The capacity of an LT-type vehicle is 5 to 10 tons. The capacity of an HT-type vehicle is 15 to 20 tons. LT and HT-type vehicles are available without any shortage. The amount of carbon emission for LT and HT-type vehicles is 0.01 to 0.02 kg/km and 0.03 to 0.04 kg/km, respectively.

7 Results and discussion

The methodology used to reconfigure the existing supply chain network for the procurement of food grains and the development of schedules for procurement centers is explained with the help of Fig. 6, as shown below. The clustering of villages is carried out by using the mathematical model presented in Sect. 4.1. Initially, the model is solved by considering one procurement center in each cluster; if in a particular cluster the distance between the village and the procurement center is more than the prescribed distance (i.e., 12.5 km), then the model is again solved by increasing the number of procurement centers in that cluster by one unit. The newly computed procurement center in each cluster ensures that farmers do not travel more than the recommended distance while selling their produce. The villages are divided into 6 clusters, and these clusters have 9, 10, 12, 9, 9, and 8 villages, respectively. “Appendix A” section presents the cluster details, and Fig. 4 exhibits their visual representation. Section 4.1

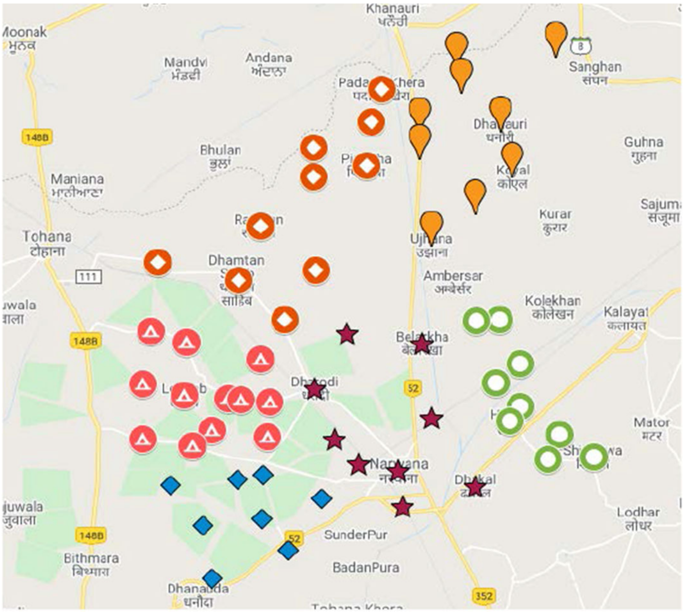

Fig. 4 Clustering of Villages of a district of North India. Cluster 1: brown, cluster 2: maroon, cluster 3: pink, cluster 4: blue, cluster 5: yellow, cluster 6: light green. (Color figure online)

offers the optimal number of procurement centers in each cluster suggested by the study model.

The details of the computed numbers of procurement centers are given in "Appendix B" section, and the pictorial representation is shown in Fig. 5. The relationship between the number of procurement centers and the total distance between the newly computed procurement center and all villages assigned in a cluster is shown in Fig. 7. These results indicate that as the number of procurement centers in a cluster increases, the total distance between the procurement center and all the villages in that cluster decreases. In the present work, the procurement centers are decided by keeping the distance between the procurement center and the villages in the range of 12.5 km. It may further be noted that the fixed cost of the procurement center increases as the number of procurement centers increases. Hence, the holistic view of the supply chain network for food grain procurement is considered for reconfiguring the entire supply chain network. By keeping this in view, these procurement centers are regarded as the input information, and the supply chain network is reconfigured by using the MILP model explained in Sect. 4.2 (Figs. 6 and 7).

The supply chain reconfiguration model explained in Sect. 4.2 is demonstrated by using a case study of a district of North India as defined in Sect. 5. The relationship among different types of costs included in the objective function Equation is shown in Fig. 8. It indicates that transportation cost plays a significant role in the entire supply chain network to procure food grains. Facility location cost and operational cost are the following tttcomponents that significantly affect the total supply chain network cost.

The utilized capacities of all established procurement centers are shown in Fig. 9. It indicates that procurement centers 1 and 2 (i. e. PC1 and PC2) are highly utilized, and the utilized capacities of the rest of the procurement centers are almost in the same range.

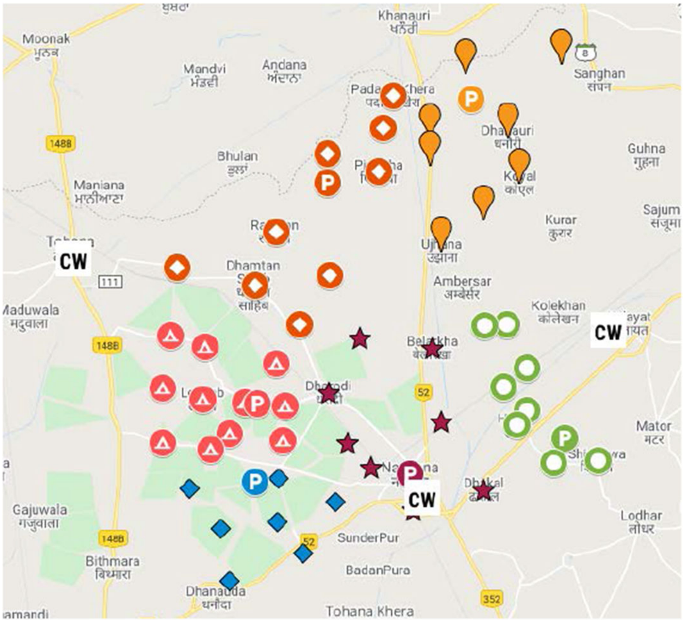

Fig. 5 Procurement centers and central warehouses of a district of North India. Cluster 1: brown, cluster 2: maroon, cluster 3: pink, cluster 4: blue, cluster 5: yellow, cluster 6: light green. (Color figure online)

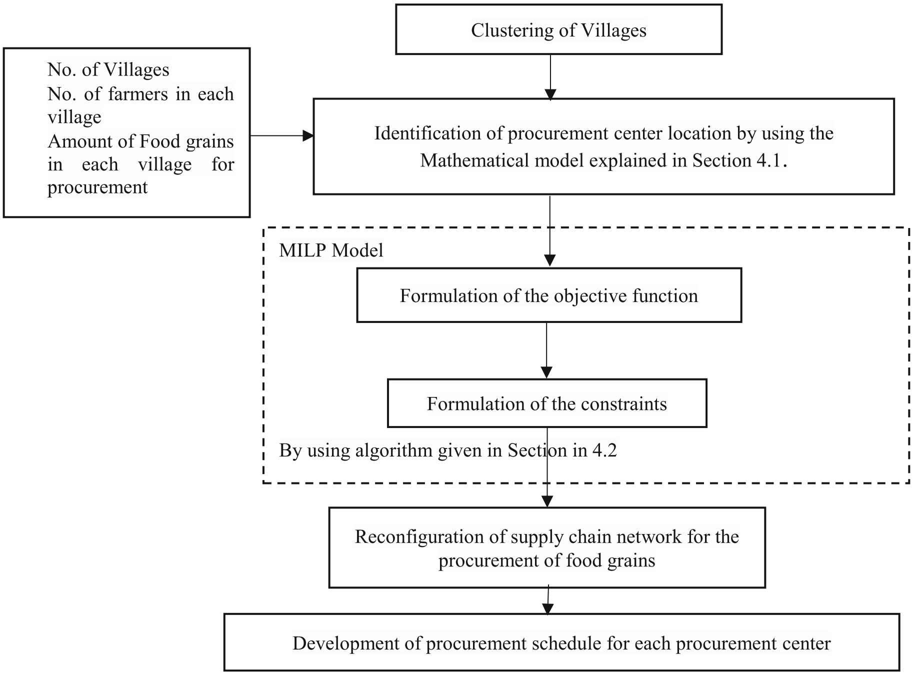

Fig. 6 Flow chart for the reconfiguration of the supply chain network & development of schedule

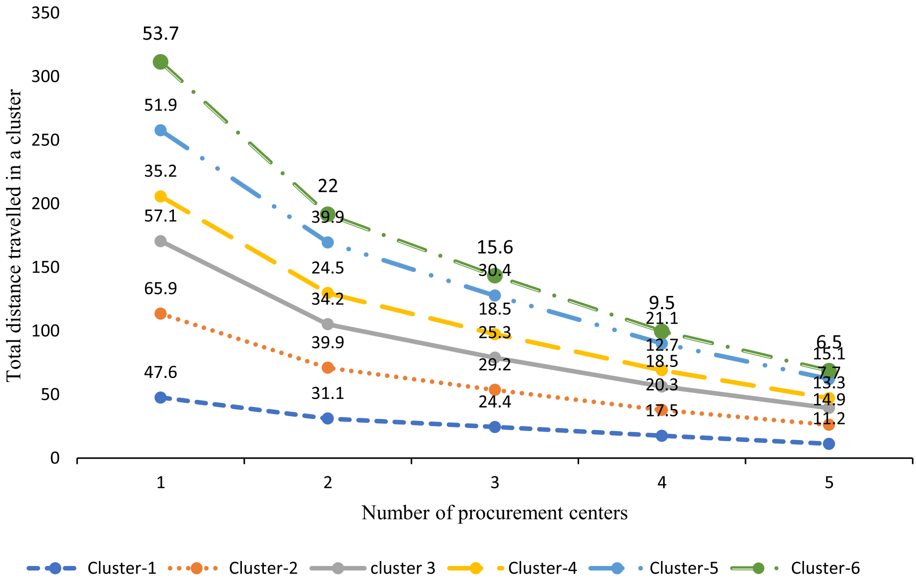

Fig. 7 In a cluster, the number of procurement centers and the total transport distance between villages and the procurement center

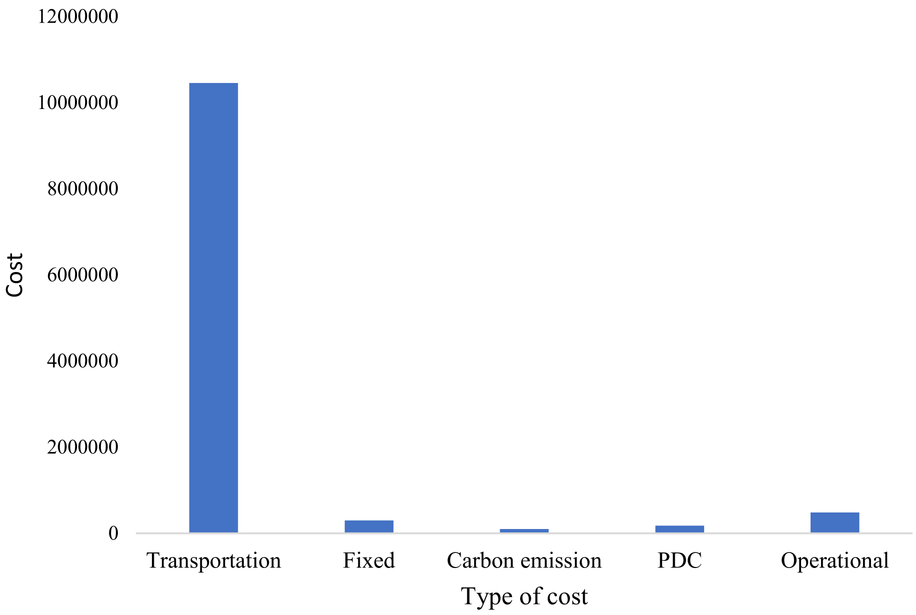

Fig. 8 Relationship between different types of costs included in the objective function equation

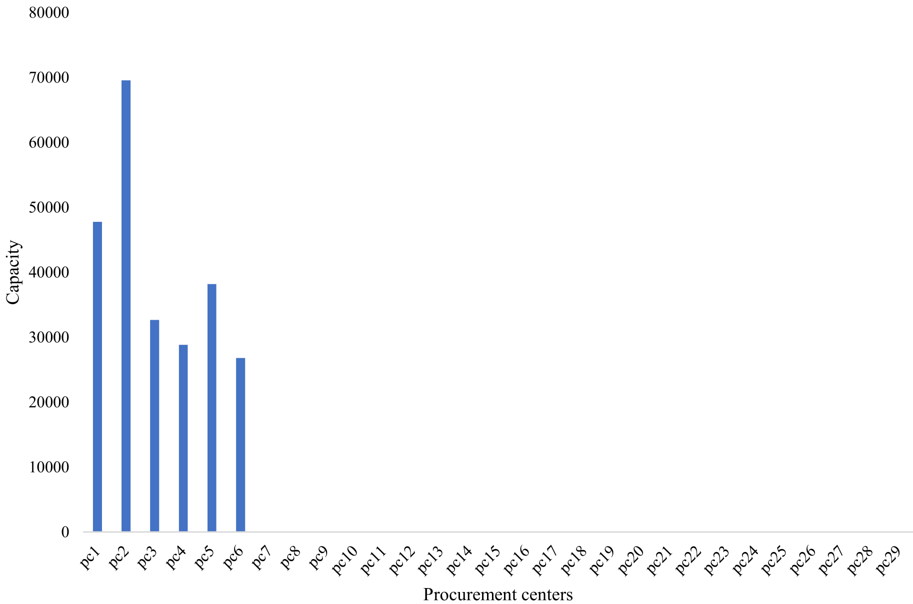

Fig. 9 The capacity of procurement centers

The effect of the number of procurement centers on transportation cost, fixed cost, carbon emission cost, social distancing cost, and total supply chain network cost is shown in Fig. 10. Figure 10 reveals that as the number of procurement centers increases the transportation cost, fixed facility cost, carbon emission cost, and total transportation cost. However, Fig. 7 shows that as the number of procurement centers in a cluster increases the total traveling distance of the farmers in that cluster decreases. These observations indicate that the number of facilities in a supply chain network should be decided by considering the holistic view of the supply chain network rather than deciding piecemeal. Hence, the supply chain network for the procurement of food grains is reconfigured by considering the holistic view of the supply chain network.

The procurement center-wide schedule for villages assigned to a specific procurement center is generated, as shown in Fig. 11. The schedule indicates that the procurement cycle time is 96, 139, 66, 58, 77, and 54 days for procurement centers PC_1, PC_2, PC_3, PC_4, $PC_{5,}$ and PC_6. The cycle time for procurement center P_2 looks pretty high. Hence, the model is again solved by increasing the procurement center by one unit to get cash without delay after selling their products under the pandemic crisis.

The modified procurement schedule is developed, as shown in Fig. 12. Figure 12 indicates that the center-wide procurement cycle time is 96, 33, 107, 66, 58, 77, and 54 days for procurement centers PC_1, PC_2, PC_2', PC_3, PC_4, $PC_{5,}$ and $PC_{6,}$ respectively.

7.1 Theoretical contributions

The present study contributes to the extant literature in several ways. First, the supply chain network for the procurement of food grains developed in the current research considers personal distancing and procurement cycle time constraints, which are unique and have

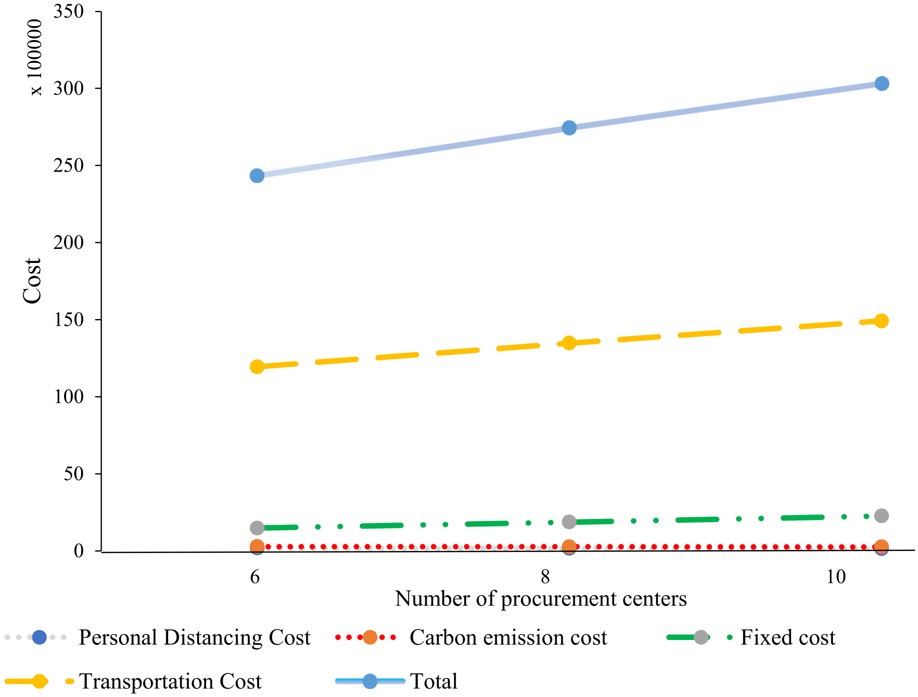

Fig. 10 Effect of no. of procurement centers on transportation, carbon emission, and total costs

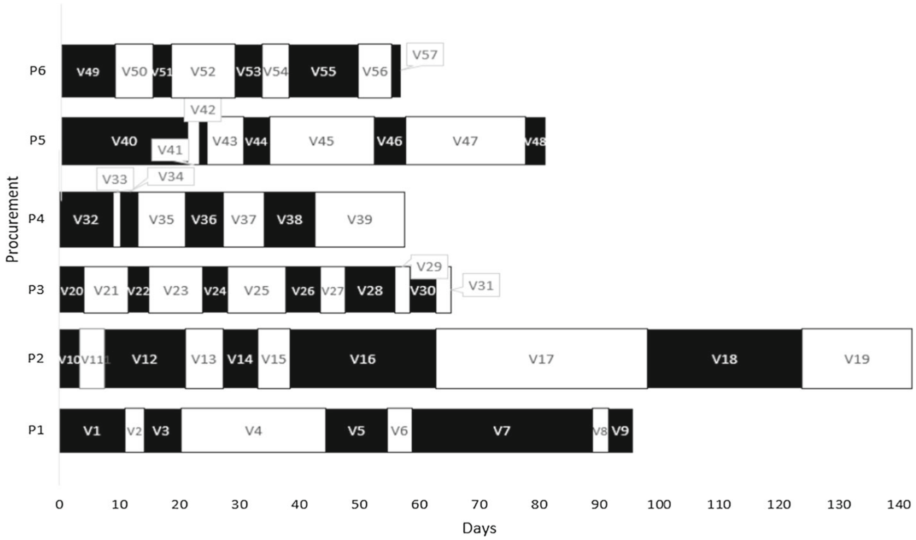

Fig. 11 Procurement schedule

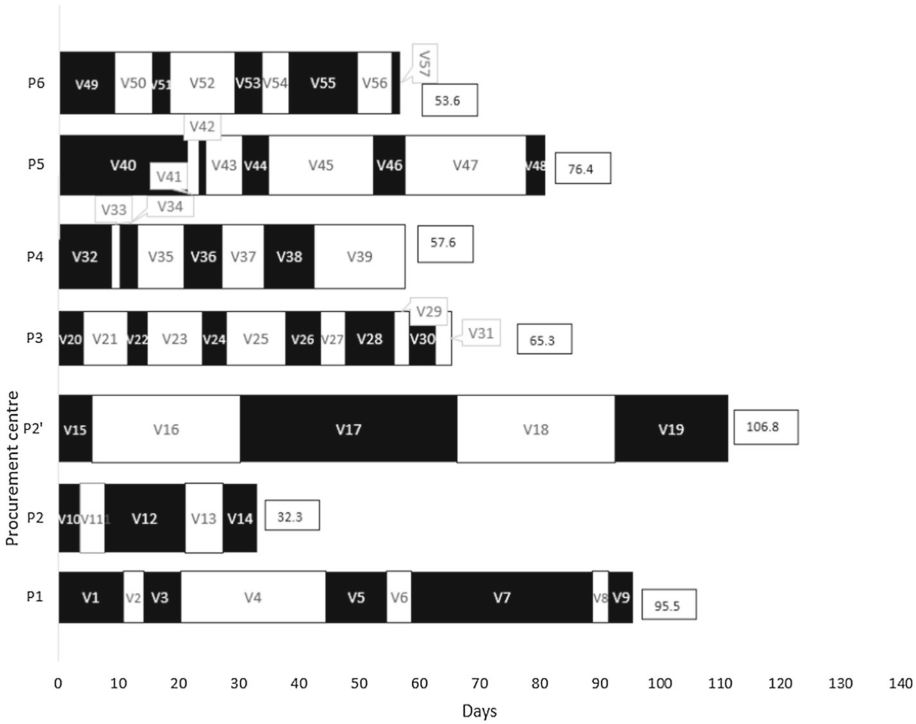

Fig. 12 Modified procurement schedule after increasing the procurement center

not been considered in the existing literature. These constraints are significant during the pandemic epidemic like the COVID-19 outbreak. Second, the study presents a novel hybrid approach for procuring food grains that ensures a selling facility for farmers within the recommended distance from their villages. Third, the study impresses the importance of an information technology-enabled strategy for designing the supply chain network from the farmers as information flows to the farmers in advance through mobile messaging. The fact that food waste is a moral issue and about 24% of the crops get wasted in the post-harvest stage further impresses the relevance of the present study. (Xue et al., 2017). Moreover, farmers are considered the most vulnerable compared to other actors in the supply chain since they are susceptible to more significant loss and have lesser control over product prices (Weinberger et al., 2008). Therefore, designing a supply chain network that ensures safe and reasonable procurement of food grains from farmers in the wake of the pandemic is of immense importance for the wellbeing of farmers and the overall food security of the state.

7.2 Managerial implications

As the supply chain network for the procurement of food grains was developed by incorporating government-issued guidelines, managers will benefit during a pandemic emergency. Plausibly, this model can allow government and non-government functionaries to engage in an optimal procurement process during pandemics. The model is very flexible, as managers may change input parameters such as the number of procurement centers, the distance constraints of villages, the procurement cycle time, and personal distancing constraints, and can develop the modified network as per their choice and can use the modified supply chain network as per their requirement. Therefore, the reliability and validity of the model remain even in varied contexts. Further, the reconfigured supply chain network minimizes transportation cost, fixed facility cost, carbon emission cost, operational cost, and personal distancing cost. Hence, procurement can be conducted with appropriate fiscal prudence, environment prudence, and health prudence.

Procurement center managers can develop a schedule, which is very useful for managing the activities of the procurement center and is also beneficial for the farmers, as they are informed in advance and can evade haphazard procurement of food grains. Specifically, administrators and managers responsible for procurement may use mobile messaging or WhatsApp messaging to farmers to allocate time to farmers for entering procurement centers. Given the development of schedules based on regional patterns, one can also provide input to farmers to schedule their harvesting on a given day. It can result in better supply chain performance. Several law and order situations that arise due to mismanaged and chaotic procurement in emerging economies can be avoided if the scheduling is done appropriately and conveyed on time. Using this model, managers can help farmers realize the best returns from their products quickly and prevent the pandemic spread. Moreover, setting procurement centers with the consideration of pandemic-related rules would create awareness among the farmers. Any information about new rules and regulations would be effectively disseminated with the farmers. Finally, given that our model considers villages assigned to procurement centers, ad procurement centers are assigned to a central warehouse to minimize the fixed facility cost. Hence, future needs for procurement canters and central warehousing can also be optimized.

7.3 Public policy implications

The issue of food waste in the supply chain is multifaceted (Schanes et al., 2018) and requires attention from all the stakeholders such as farmers, policymakers, and managers. Policymakers should focus on reducing post-harvest losses; hence, it is recommended to improve the storage facilities. This study indicates that policymakers should provide easy market access for food grains by opening adequate numbers of food grains procurement centers in the surplus state. The policymakers should rapidly establish these procurement centers, keeping in mind farmers' inadequate space for storing their harvest and cash crunch. Village roads and transportation must be improved to bring their harvest to procurement centers at minimum cost. The same is true for the roads and transport facilities from procurement centers to warehouses. All the above steps can further reduce the cost of the supply chain network for the procurement of food grains.

A much-appreciated step by the government of India is the introduction of the FASTag system at toll booths, which reduces transportation time, fuel costs, and carbon emissions. The present study's findings underline the importance of a collaborative strategy for the farmers, policymakers, and managers. The model developed should be adopted to create shared value for the supply chain actors and society. The policymakers can also leverage the present study's findings to drive systemic change towards the achievement of *Sustainable Development Goals* (SDGs) (United Nations, 2015). The government is already on efforts to reduce the amount of wasted edible food to achieve the target of SDG-12 that involves food waste reduction. The establishment of procurement centers so that the farmers do not have to travel long distances would help to reduce the post-harvest losses and prevent the possible transmission of COVID-19.

8 Conclusion, limitation, and future scope

The present research reconfigures the existing supply chain network to procure food grains under the COVID-19 outbreak to support the worldwide personal distancing constraint. The reconfiguration of the supply chain network is carried out in two steps. In the first step, a given number of procurement centers are decided on, based on a distance constraint between villages and procurement centers determined using a mathematical model as explained in Sect. 4.1. In the second step, villages are assigned to procurement centers, and procurement centers are set to a central warehouse to minimize the fixed facility cost, transportation cost from village to procurement center, transportation cost from the procurement center to the central warehouse, and carbon emission and social distancing cost. Thus, the proposed reconfiguration supply chain network could help policymakers determine the infrastructure of supply chain networks and farmers for selling their harvest and getting cash without delay during the countrywide lockdown due to the COVID-19 outbreak.

A rational being tends to improve the current practice in place through continuous research. Selection of procurement centers and further procurement of food grains under dynamic circumstances like the COVID-19 outbreak will play a significant role in reconfiguring the existing food grain supply chain network. Policymakers have given this aspect attention in recent months. The current multifaceted problems and their complex nature due to the COVID-19 outbreak have spurred these researchers to reconfigure the existing supply chain network to procure food grains. The study could be extended in various ways. First, a more significant number of case studies will provide a base for more case studies to come. Moreover, further research could consider other hybrid methodologies for the reconfiguration of the supply chain network. Furthermore, the distribution segment of the supply chain network could be studied under the present COVID-19 outbreak separately. Additionally, the segment that is a part of distribution could be added to the whole procurement process, and both procurement and allocation can be assessed together again. The management of the food grain supply chain in the wake of COVID-19 is a contingent matter. However, its long-term impacts are yet to unfold. Future researchers will need more attention to facilitate the transition to a technology-enabled and resilient food grain supply chain.

Appendix A: Clusters of villages

	Villages	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9
Cluster 1 (Brown)	V_1	0	7.8	8.5	6.4	8.7	11.8	14.8	12.3	11.3
	V_2	7.8	0	2.7	6.1	9	9.2	12.8	6.5	5
	V_3	8.5	2.7	0	3.3	6.3	6.4	11.5	5.2	3.7
	V_4	6.4	6.1	3.3	0	3.2	4.1	12.7	6.3	7.1
	V_5	8.7	9	6.3	3.2	0	3.6	6.6	9	10
	V_6	11.8	9.2	6.4	4.1	3.6	0	9.7	8.8	10.2

	Villages	V_1	V_2	V_3	V_4	V_5	V_6	V_7	V_8	V_9
	V_7	14.8	12.8	11.5	12.7	6.6	9.7	0	6.3	8.1
	V_8	12.3	6.5	5.2	6.3	9	8.8	6.3	0	1.7
	V_9	11.3	5	3.7	7.1	10	10.2	8.1	1.7	0

	Villages	V_{10}	V_{11}	V_{12}	V_{13}	V_{14}	V_{15}	V_{16}	V_{17}	V_{18}	V_{19}
Cluster 2 (Maroon)	V_{10}	0	2.4	5	7.4	8.5	13	13.3	17	16.6	21.3
	V_{11}	2.4	0	2.8	6.4	6.3	10.8	11.2	14.9	14.5	19.2
	V_{12}	5	2.8	0	5	3.4	7.9	8.3	12	11.6	16.3
	V_{13}	7.4	6.4	5	0	2.1	6.6	10.6	10.7	13.3	15
	V_{14}	8.5	6.3	3.4	2.1	0	4.5	8.5	8.6	11.2	12.8
	V_{15}	13	10.8	7.9	6.6	4.5	0	4.3	4.4	7.1	8.6
	V_{16}	13.3	11.2	8.3	10.6	8.5	4.3	0	5.4	3.3	12.6
	V_{17}	17	14.9	12	10.7	8.6	4.4	5.4	0	8.1	5.8
	V_{18}	16.6	14.5	11.6	13.3	11.2	7.1	3.3	8.1	0	15.3
	V_{19}	21.3	19.2	16.3	15	12.8	8.6	12.6	5.8	15.3	0

	Villages	V_{20}	V_{21}	V_{22}	V_{23}	V_{24}	V_{25}	V_{26}	V_{27}	V_{28}	V_{29}	V_{30}	V_{31}
Cluster 3 (Pink)	V_{20}	0	2.5	8.7	9.7	8.1	6.7	6.2	3.6	7.4	9.5	8.7	11.6
	V_{21}	2.5	0	6.1	7	5.4	4.1	3.5	6.3	7.5	6.8	6.1	9
	V_{22}	8.7	6.1	0	3	4.1	5.3	5.6	8.4	9.5	8	7.3	5
	V_{23}	9.7	7	3	0	2.1	2.9	5.8	8.6	9.8	8.3	7.6	2.6
	V_{24}	8.1	5.4	4.1	2.1	0	1.3	4.2	7	8.2	6.7	6	4
	V_{25}	6.7	4.1	5.3	2.9	1.3	0	2.9	5.7	6.9	5.4	4.7	4.8
	V_{26}	6.2	3.5	5.6	5.8	4.2	2.9	0	3	4.2	4.2	3.5	7.7
	V_{27}	3.6	6.3	8.4	8.6	7	5.7	3	0	3.8	6.7	6	10.6
	V_{28}	7.4	7.5	9.5	9.8	8.2	6.9	4.2	3.8	0	3.9	6.2	9.1
	V_{29}	9.5	6.8	8	8.3	6.7	5.4	4.2	6.7	3.9	0	2.3	5.5
	V_{30}	8.7	6.1	7.3	7.6	6	4.7	3.5	6	6.2	2.3	0	5.4
	V_{31}	11.6	9	5	2.6	4	4.8	7.7	10.6	9.1	5.5	5.4	0

	Villages	V_{32}	V_{33}	V_{34}	V_{35}	V_{36}	V_{37}	V_{38}	V_{39}
Cluster 4 (Blue)	V_{32}	0	1.8	7	5.7	6	5.5	4.7	8.4
	V_{33}	1.8	0	5	7.4	4.5	3.6	6.4	6.5
	V_{34}	7	5	0	11.9	8	5	11.4	9.5

	Villages	V_{32}	V_{33}	V_{34}	V_{35}	V_{36}	V_{37}	V_{38}	V_{39}
	V_{35}	5.7	7.4	11.9	0	7.5	11	6	11.4
	V_{36}	6	4.5	8	7.5	0	4.2	2.3	6.2
	V_{37}	5.5	3.6	5	11	4.2	0	10	5.8
	V_{38}	4.7	6.4	11.4	6	2.3	10	0	5.8
	V_{39}	8.4	6.5	9.5	11.4	6.2	5.8	5.8	0

	Villages	V_{40}	V_{41}	V_{42}	V_{43}	V_{44}	V_{45}	V_{46}	V_{47}	V_{48}
Cluster 5 (Yellow)	V_{40}	0	8.5	5	7.7	10.7	13.1	15.2	12.4	7.7
	V_{41}	8.5	0	5.5	7.8	8.3	13.5	15.6	12.9	8.1
	V_{42}	5	4.3	0	2.7	5.4	7.5	12	9.3	4.5
	V_{43}	7.7	5	2.7	0	2.7	6.1	14.8	12.1	7.2
	V_{44}	10.7	8.3	5.4	2.7	0	3.4	12.8	17	10
	V_{45}	13.1	13.5	7.5	6.1	3.4	0	10.8	14.7	10
	V_{46}	15.2	15.6	12	14.8	12.8	10.8	0	16	10.3
	V_{47}	12.4	12.9	9.3	12.1	17	14.7	16	0	4.7
	V_{48}	7.7	8.1	4.5	7.2	10	10	10.3	4.7	0

	Villages	V_{49}	V_{50}	V_{51}	V_{52}	V_{53}	V_{54}	V_{55}	V_{56}	V_{57}
Cluster 6 (Light Green)	V_{49}	0	3	3.5	6.1	6.5	14.9	12.3	16.5	15.5
	V_{50}	3	0	2.2	3.2	3.6	12	9.5	13.6	12.6
	V_{51}	3.5	2.2	0	4.6	4.1	9.9	7.4	11.5	10.5
	V_{52}	6.1	3.2	4.6	0	0.4	10.6	8	12.2	11.2
	V_{53}	6.5	3.6	4.1	0.4	0	11	8.4	12.6	11.6
	V_{54}	14.9	12	9.9	10.6	11	0	2.6	5.9	4.9
	V_{55}	12.3	9.5	7.4	8	8.4	2.6	0	4.2	3.2
	V_{56}	16.5	13.6	11.5	12.2	12.6	5.9	4.2	0	1.3
	V_{57}	15.5	12.6	10.5	11.2	11.6	4.9	3.2	1.3	0

Appendix B: Procurement center and central warehouse distance matrix

Central Warehouses	Procurement centers					
	V_3	V_{14}	V_{24}	V_{33}	V_{42}	V_{51}
CW1	36	20	16.7	20.5	28.7	43.4
CW2	29.5	27.4	14	11.7	2.3	12.5
CW3	17.8	27.4	32.9	28.7	20	9.2

Appendix C: Number of farmers in each village

Sr. No	Villages	Number of farmers	Sr. No	Villages	Number of farmers	Sr. No	Villages	Number of farmers
1	V_1	1090	20	V_{20}	415	39	V_{39}	1509
2	V_2	328	21	V_{21}	736	40	V_{40}	2004
3	V_3	611	22	V_{22}	337	41	V_{41}	185
4	V_4	2418	23	V_{23}	910	42	V_{42}	116
5	V_5	1016	24	V_{24}	401	43	V_{43}	577
6	V_6	413	25	V_{25}	983	44	V_{44}	407
7	V_7	3005	26	V_{26}	571	45	V_{45}	1653
8	V_8	271	27	V_{27}	414	46	V_{46}	495
9	V_9	404	28	V_{28}	825	47	V_{47}	1897
10	V_{10}	344	29	V_{29}	250	48	V_{48}	308
11	V_{11}	401	30	V_{30}	434	49	V_{49}	865
12	V_{12}	1308	31	V_{31}	255	50	V_{50}	593
13	V_{13}	619	32	V_{32}	886	51	V_{51}	284
14	V_{14}	561	33	V_{33}	141	52	V_{52}	1013
15	V_{15}	541	34	V_{34}	287	53	V_{53}	425
16	V_{16}	2363	35	V_{35}	782	54	V_{54}	425
17	V_{17}	3459	36	V_{36}	629	55	V_{55}	1086
18	V_{18}	2516	37	V_{37}	699	56	V_{56}	535
19	V_{19}	1802	38	V_{38}	831	57	V_{57}	138

Appendix D: Temporary purchasing center

Sr. No.	Procurement center	Sr. No.	Procurement center	Sr. No.	Procurement center	Sr. No.	Procurement center	Sr. No.	Procurement center
1	P_1	7	P_7	13	P_{13}	19	P_{19}	25	P_{25}
2	P_2	8	P_8	14	P_{14}	20	P_{20}	26	P_{26}
3	P_3	9	P_9	15	P_{15}	21	P_{21}	27	P_{27}
4	P_4	10	P_{10}	16	P_{16}	22	P_{22}	28	P_{28}
5	P_5	11	P_{11}	17	P_{17}	23	P_{23}	29	P_{29}
6	P_6	12	P_{12}	18	P_{18}	24	P_{24}		

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