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ORIGINAL PAPER

Restructuring the Indian agro-fresh food supply chain network: a mathematical model formulation

Rakesh Patidar[1] · Sunil Agrawal[1]

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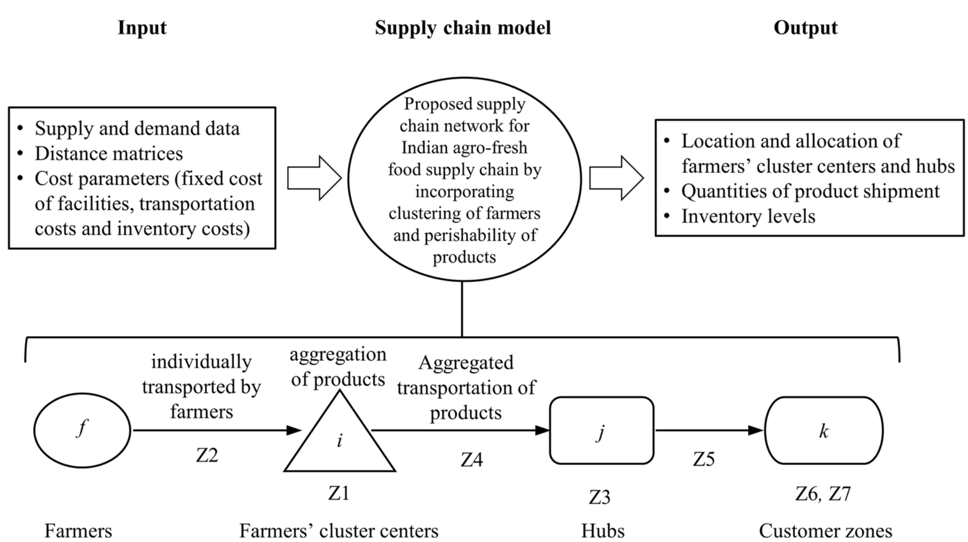
Abstract
In traditional Indian agro-fresh food supply chain (AFSC), authors identify the following four shortcomings through the literature survey: (1) unorganized supply chain structure; (2) low profitability of farmers; (3) high wastage of agricultural products; and (4) a large number of small-farm-holding farmers. According to the fourth shortcoming, 85% of farmers have less than 2 hectares of farming land, and these farmers transport their products independently into the market to sell. Owing to this, a higher transportation cost is incurred in traditional AFSC, which leads to low profit for farmers. To overcome these shortcomings, authors propose aggregation of products by forming clusters of farmers and its transportation from these cluster centers to market. This paper formulates multi-period, multi-product, mixed-integer nonlinear programming model to design a four-echelon supply chain with considering the clustering of farmers and perishability of products. A real case study problem of Mandsaur District (India) of vegetable distribution is solved in LINGO 17.0 to check the validity of the formulated model. The results revealed that 85% of the total distribution cost incurred in the transportation of products from farmers to the market. Hence, the major focus should be to design an efficient transportation plan for the minimization of transportation cost from farmers to the market. Further, sensitivity analysis shows that the proposed model is robust and sensitive to changes in maximum distance traveled by a farmer to reach a cluster center and number of hubs to be opened, respectively.

Graphic abstract



Keywords Agro-fresh food supply chain (AFSC) · Supply chain network (SCN) · Perishability · Aggregate product transportation · Mixed-integer nonlinear programming (MINLP)

Extended author information available on the last page of the article

List of symbols

Indices

f Index of farmers (suppliers), $f \in \{1, .., F\}$
i Index of FCCs, $i \in \{1, .., I\} \in F$
j Index of hubs, $j \in \{1, .., J\}$
k Index of CZs (retailers), $k \in \{1, .., K\}$
p Index of product types, $p \in \{1, .., P\}$
t, τ Index of periods, $t \in \{1, .., T\}$

Parameters

H_{fp}^{t} The harvested quantity of product type p available to supply from fth farmer (kg)
l_p The shelf life of product type p (period)
D_{kp}^{t} The quantity demanded at kth CZ for product type p (kg)
$D1_{fi}$ Distance from farmer fth to ith FCC (km)
$D1_{\mathrm{m}}$ Maximum distance to be traveled by a farmer to belong to any FCC (km)
$D2_{ij}$ Distance from ith FCC to jth hub (km)
$D3_{jk}$ Distance from jth hub to kth CZ (km)
TC_1 Unit transportation cost from a farmer to an FCC [INR (The current value of 1 INR is equal to 0.014 USD as on September 10, 2020)/km/kg]
TC_2 Unit transportation cost from an FCC to a hub(INR/km/kg)
TC_3 Unit transportation cost from a hub to a CZ (INR/km/kg)
HC_{kp} Per period inventory holding cost of product type p at kth CZ (INR/kg/period)
LB_{ip} Lower bound on supply from ith FCC to hub(s) for product type p (kg)
LB_{jp} Lower bound on supply from jth hub to CZ(s) for product type p (kg)
NH Number of hubs to be opened
$\mathrm{FC1}_i$ Fixed cost of forming ith FCC (INR)
$\mathrm{FC2}_j$ Fixed cost for opening jth hub (INR)
DC_p Disposal cost of expired product type p (INR)
M Big number

Decision variables

F_i^t $\begin{cases} 1 & \text{if } i\text{th FCC is formed in period } t; \\ 0 & \text{otherwise.} \end{cases}$
Y_{fi}^t $\begin{cases} 1 & \text{if } f\text{th farmer is assigned to } i\text{th FCC in period } t; \\ 0 & \text{otherwise.} \end{cases}$
Z_j^t $\begin{cases} 1 & \text{if } j\text{th hub is opened in period } t; \\ 0 & \text{otherwise.} \end{cases}$
Q_{ijp}^t Quantity of product type p shipped from ith FCC to jth hub in period t (kg)
$Q_{jkp}^{\prime t\tau}$ Quantity of product type p shipped from jth hub to kth CZ in period t for use in period τ ($\tau \geq t$) (kg)
I_{kp}^t Inventory of product type p at kth CZ in period t (kg)
Ex_{kp}^t Quantity of the to be expired product type p supplied in period t by any hub to kth CZ (kg)

Introduction

A supply chain (SC) is a sequence of processes and flows which take place within and between different players. It consists of all parties involved, directly or indirectly, in fulfilling a customers' request (Chopra and Meindl 2007). An agro-fresh food supply chain (AFSC) includes all the processes from production (farmer) to delivery (customer) of short shelf life items (Shukla and Jharkharia 2013). A successful AFSC delivers the daily demanded fresh items at the lowest possible cost. It not only ensures the profitability of stakeholders but also focuses on less wastage by fast delivering fresh items to the customers. The structure of the supply chain network (SCN) plays a vital role in achieving the above objectives. AFSC in India lacks these objectives due to various unfathomable problems in the chain. Therefore, it is unsustainable for the farmers and is required to be reformed by solving real-life problems.

Structure of traditional Indian AFSC is shown in Fig. 1. The working of this SC is explained as follows: farmers grow crops based on their perception about future demand. After harvesting, they bring their products individually by using owned or hired vehicle(s) into the agricultural market to sell. The agriculture market (mandi) is a regulated market that is ruled by the Agriculture Produce Marketing Committee (APMC) under the state government regulation. In this market yard, a commission agent does an open auctioning, and the wholesaler buys these items through bidding the highest price in the auctioning. Subsequently, the retailers purchase these items from the wholesaler in small quantities. Finally, retailers sell the items to the customers by opening a temporary shop on the street or visiting the proximity locations of

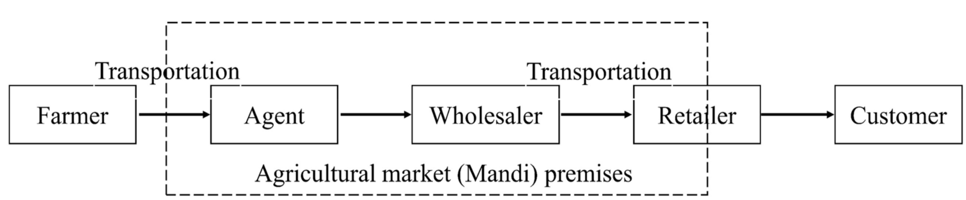


Fig. 1 Structure of traditional Indian AFSC

customers (Panda and Sreekumar 2012; Hegde and Madhuri 2013; Patidar et al. 2018a). The players between farmers and customers, i.e., agents, wholesalers, and retailers, are known as intermediaries in the chain.

The motivation behind the organizing and restructuring of SCN comes from the key shortcomings of traditional Indian AFSC, and these are as follows: (1) unorganized SC structure; (2) low profitability of farmers; (3) high wastage of agricultural products; and (4) a large number of small-farm-holding farmers. The description of these shortcomings is discussed in the below sections.

Unorganized SC structure

A comparative study of AFSCs across the world (developed versus developing countries) with special reference to India is presented by Samuel et al. (2012). The study discussed an insight into evolution, procurement, marketing strategies, and business models to provide an overview of varied existing AFSCs and compare SC structures across the world. Organized retailing has evolved in the UK,USA, Australia, New Zealand, and China. AFSC in Indian context is unstructured and mainly dominated by a large number of unorganized intermediaries. Thereby, the traditional Indian AFSC is unorganized and mainly governed and controlled by a large number of unorganized intermediaries. The pricing of products is decided by the unorganized intermediaries who play their monopoly in auctioning (Viswanadham et al. 2012). These intermediaries add service charges and profit margins into the price of the products. There is a lack of competitive environment in the chain that results in a higher price of the product. There is no direct communication between the farmers and the customer. However, in recent times, several information and communication technology (ICT) initiatives are implemented to improve communications amongst the different SC actors (Dandage et al. 2017). Further, the unorganized SC structure causes a longer delivery lead time and results in degradation of product quality in terms of its freshness with a large amount of wastage (Rajkumar 2010).

Low profitability of farmers

The unorganized SC structure and presence of a large number of intermediaries result in low profitability of farmers. Another reason for the low profitability of farmers can be understood through a set of studies (Raghunath and Ashok 2009; Panda and Sreekumar 2012; Hegde and Madhuri 2013; Kundu 2013). These authors examined the traditional AFSC and reported that individually farmers transport their products into market premises to sell. In this process, farmers manage and pay the cost of transportation facilities. Farmers feel this as a hurdle in every visit to the market. Due to this, they are forced to sell their products to local intermediaries rather than selling into the regulated market or mandi. Finally, farmers are deprived of higher prices of products and the profit margins are taken by intermediaries. This results in customers paying the higher prices of products and farmers receiving the only one-third prices paid by the customers. The third reason for the low profitability of farmers is continuously rising prices of input resources like fuel, fertilizers, pesticides, farm equipment, labor, whereas average prices of agricultural products are not increased in the proportional increase in the prices of the input resources. Thus, farming is not a profitable business for the farmers' community. Therefore, farmers are continuously demanding profitable (or at least better) prices of the crops and many times they agitate against the government to raise the issue of poor pricing of products (Hindustan Times 2017).

High wastage of agricultural products

The third main problem in Indian AFSC is the high wastage of agricultural products as identified in a set of papers (Balaji and Arshinder 2016; Gardas et al. 2017, 2018; Gokarn and Kuthambalayan 2017). According to these papers, 15–25% of fresh items are lost due to improper storage and handling, poor SCN design, presence of a large number of intermediaries, and lack of demand–supply integration. Further, this wastage results in low profitability of farmers, decrease in nutrition level, increase in the prices of products, and non-productive use of natural resources. Another cause of food wastage is the inherent characteristic of fresh items, i.e., perishable nature of products.

A large number of small-farm-holding farmers

The continuous population growth leads to family expansion and other infrastructural development. Due to these, the average agricultural landholding per family has been reduced from 2.28 hectares in 1970–71 to 1.16 hectares in 2010–11. Hence, the small farmers—having farming land less than 2 hectares—have been increased from 70% to 85% from the years 1970–71 to 2010–11 (NABARD 2014). The small farmers are the residence of geographically scattered rural areas. In the scattered production scenario, most of the farmers bring their product individually in the agriculture market by traveling long distances, as discussed in "Low profitability of farmers" section. This increases the overall transportation cost in the SC, which is in the range of 30–40% of total transaction costs (Panda and Sreekumar 2012; Hegde and Madhuri 2013).

Research gap

A set of review papers (Rajurkar and Jain 2011; Samuel et al. 2012; Dandage et al. 2017; Gardas et al. 2017; Negi and Anand 2017; Siddh et al. 2017) identified operational issues like lack of loading–unloading facilities, appropriate packing methods, tracking, and traceability facilities due to improper SCN. These articles revealed that although a lot of research work in the field of AFSC had been done in the past, yet the organizing and restructuring of the chain for perishable products in the Indian context was overlooked by the researchers. Unanimously, the authors recommended designing an appropriate SCN model for Indian AFSC. However, few researchers (Anjaly and Bhamoriya 2011; Kundu 2013; Sihariya et al. 2013; Sohoni and Joshi 2015) discussed the case study-based conceptual model for the distribution of fresh produce. Recently, Patidar et al. (2018a) analyzed the Indian AFSC and reported that the improper SCN model is responsible for high wastage of produce and low profitability of farmers. The authors suggested developing a suitable model for the integration of small farmers and aggregate product transportation from farmers to market. Additionally, the perishability of items was identified as the main challenge in SCN modeling to reduce food waste in Indian AFSC (Gokarn and Kuthambalayan 2017). Hence, the designing of the SCN model for the Indian scenario is a crucial requirement in order to solve identified shortcomings (sections "Unorganized SC structure" to "A large number of small-farm-holding farmers").

The efficient transportation of products from small scattered farmers to market can mitigate the identified shortcomings. However, it is not feasible for retailers or wholesalers to collect the products directly from geographically scattered small farmers (Trebbin 2014). A possible solution to the above shortcomings is proposed in this paper by considering aggregate product transportation from cluster centers to market. Defining the clustering of farmers is the first and foremost task for aggregate product transportation. It also enables the farmers to participate in competitive SC in a consolidated form. The aggregate product transportation and perishability consideration in the proposed model have capabilities to address the following three aspects of sustainability: first, the aggregate product transportation by clustering of farmers is capable to reduce the transportation cost (economic aspect). Second, the reduced transportation cost can be realized by farmers, which increases the farmers' profitability (social aspect). Third, the perishability consideration in the proposed model will determine to be expired products in advance. These excess products can be supplied to other institutional demand nodes (like hospitals, hostels, and restaurants) in less price; thus, it will reduce the wastage of agricultural products (environment aspect). The idea of aggregate product transportation in the proposed model also supports easy product handling and reduction in carbon emissions. Hence, this novel concept may reform traditional Indian AFSC by distributing fresh items in efficient and effective ways as well as reducing the actual shortcomings of the system. Therefore, the purpose of this work is to propose an environmentally sustainable SCN for Indian AFSC with considering the aggregate product transportation and perishability of products into the model.

Literature review

The SCN design is a strategic decision that identifies SC structure and configuration over the next several years by developing an appropriate mathematical model (Chopra 2003). The developed mathematical model determines the locations and allocations of facilities to serve customers' demand efficiently and effectively. Therefore, this type of model is also known as the location–allocation problem (Daskin et al. 2005; Amiri 2006). The problem can be formulated as discrete or continuous, single objective ormulti-objective, single period or multi-period, with or without the restriction of capacitated facilities(Melo et al. 2009).

To investigate the state-of-the-art in the field of the SCN models, the literature review is divided into three sections as follows: the first section discusses the papers related to the models of SC structure. The recent papers that considered perishability into the SCN models are described in the second section. The third section explains some relevant papers on aggregate product transportation and distribution in the SC models.

Single versus multi-period SCN model

Jayaraman and Ross (2003) formulated a single period, three-echelon SCN model for multi-product in two stages. The first stage determined decisions about locating facilities among the available potential locations and accordingly, assignments between these facilities were made into the second stage. Another single period, four-echelon SC model by considering hybrid and flexible multi-objective outbound logistics network for different variants of items (i.e., fast, slow, and very slow-moving items) was formulated by Hiremath et al. (2013). The proposed network was defined as hybrid and flexible by considering varying delivery lead time and possible roll-back strategy in the model. In recent years, researchers have started the designing of agriculture SCN in order to solve real-life problems by adopting the idea of SC modeling from the available literature. The integrated SCN of production and distribution for fresh items were formulated as a mixed-integer linear programming model in the set of articles (Ahumada and Villalobos 2011; Farahani et al. 2012). Etemadnia et al. (2015) designed a three-echelon wholesale hub location model for efficient distribution of locally grown fruits and vegetables in the USA.

The multi-period model helps in determining the impact of supply and demand variability with respect to time on the

SC structure, and it ascertains whether it is worth to use a more complex multi-period model for designing SCN (Melo et al. 2009). Khamjan et al. (2013) developed a mathematical model to determine the location–allocation and capacity of the existing and new sugar cane loading stations for Thailand. Gelareh et al. (2015) developed a multi-period hub location model for hub-and-spoke network structure by considering installation, maintenance, and closing costs associated with each hub. Gholamian and Taghanzadeh (2017) formulated a five-echelon wheat SCN model of Iran to determine the location–allocation decisions of various facilities with considering multi-mode transportation. In the model, the authors considered the blending of different types of wheat to produce different products with quality variations.

Perishability consideration in SCN model

After harvesting, the perishable products deteriorated with elapsed time. Over the succeeding useful shelf life, such products became expired items—that need to be disposed of—which requires an additional cost. In the literature, researchers have accounted for perishability in the following two ways: (1) continuous function of deterioration and (2) step function of deterioration. Therefore, the available literature on perishable food SC has been summarized in these two groups. Rong et al. (2011) developed a production and distribution planning model for a single product with considering continuous food quality deterioration in storage and transportation activities. The model determined the duration of storage and transportation activities together with the appropriate temperature for the different locations and transportation equipment in order to minimize the overall cost of logistics and preservation. Nourbakhsh et al. (2016) developed a mathematical model by considering quantitative and qualitative post-harvest losses in the SCN model. The model determined optimal locations of pre-processing facilities and plans for transportation and infrastructure investment by identifying roadway/railway capacity expansion. Dolgui et al. (2018) developed a mathematical model to optimize integrated production, inventory, and distribution decisions for perishable items in a multi-stage SC.

A few articles considered perishability as a step function of deterioration, which means that during the shelf life of the product, there is no deterioration, and the product can be used with the original value. After crossing the shelf life, its salvage value is zero, and the product cannot be used (a binary decision). Rahimi et al. (2017) developed a single-stage inventory-routing model for the distribution of fresh products in urban areas by considering the perishability as a step function. Recently, Savadkoohi et al. (2018) developed a three-echelon location-inventory model for the perishable pharmaceutical SC. The model determined manufacturing and distribution centers' locations, material flow in the network, and the optimal inventory policy considering the step function of perishability to minimize the total SC cost.

Ahumada and Villalobos (2009); Shukla and Jharkharia (2013); Tsolakis et al. (2014); Soto-Silva et al. (2016) reviewed agriculture SC planning models and suggested to develop appropriate SCN models by dealing with particular region-specific problems. The papers (Routroy and Behera 2017; Siddh et al. 2017) provided a structural literature review on perishable food SC and reported that the designing of SCN model for the developing countries had been given less attention in comparison with the developed countries.

Aggregate product transportation/distribution in the SCN model

The aggregate product transportation results in efficient flow of products of an SC by reducing overall transportation cost in comparison with the point to point transportation. The product aggregation can be done by forming the groups of farmers of the nearby locations. Bosona and Gebresenbet (2011) considered clustering of farmers and optimized the location of clusters to integrate the logistics activities in the local food SC. On the other hand, Boudahri et al. (2011) developed a single period, three-echelon chicken meat SC for the single product with considering clustering of customers. The authors formulated the problem in two submodels. The first model determined the centroid of customers' clusters to establish retail centers, and accordingly, the assignments were determined into the second model. Based on literature review, SC characteristics, and configuration variables, Dreyer et al. (2016) developed strategies to improve AFSC for Norwegian small-scale producers. The authors reported that farmers' clustering would help in collaboration and consolidation of volume and products, which will increase service levels and fulfill requirements by prioritizing products to sell and to what customers. Most risks in perishable SC comes from internally, and it can be mitigated by horizontal and vertical integration and collaboration among players (Ali et al. 2017). In the literature of SC models, clustering of players has not been considered in single-step SCN modeling. However, in recent years, Rancourt et al. (2015) and Khalilpourazari and Khamseh (2017) used covering radius to identify the location (out of potential site) to establish food distribution centers and temporary/permanent blood transportation facilities in disaster relief SC, respectively.

Recently, Zhu et al. (2018) reviewed the food SC models and reported that the involvement of small farmers is neglected. The small farmers have weak participation power in competitive SC. Moreover, if we look from the application point of view, clustering of farmers is an essential requirement of the system as well as it has the potential to solve the identified problems of Indian AFSC (sections "Unorganized SC structure" to "A large number of small-farm-holding farmers"). It has been identified from the literature that the clustering of farmers (suppliers) is not yet considered in the designing of SCN as reported in the above section. Therefore, it is worthwhile to propose a restructured SCN by formulating a mathematical model with considering the clustering of farmers and perishability of products.

Proposed model description and formulation

As discussed in the introduction section, the traditional Indian AFSC has an unorganized SC structure, high wastage of agricultural products, and inefficient transportation of products from small farmers to market. To organize and restructure SCN, a discrete location–allocation problem is considered to formulate the chain for perishable products. The problem is to identify the optimal locationand allocation of facilities among the set of available potentiallocations and movement of products between these facilities such that total SC cost is minimized. The complete description and formulation of the proposed restructured model for Indian AFSC are explained in the following sections.

Model description

The working of traditional Indian AFSC (Fig. 1) has been explained in the introduction section. The agents and wholesalers work at the same location inside the market premises to match demand and supply. So, authors assume both as a single SC entity as a hub to organize the SC structure. There can be multiple hubs, and the locations of these hubs can be multiple places in a region. Similarly, retailers sell products to customers by visiting customers' proximity locations. Therefore, the retailers and customers are assumed at the same echelon in the SC and named as customer zone (CZ) in the formulation. The number of CZs depends on the population of a region like wards in a city.

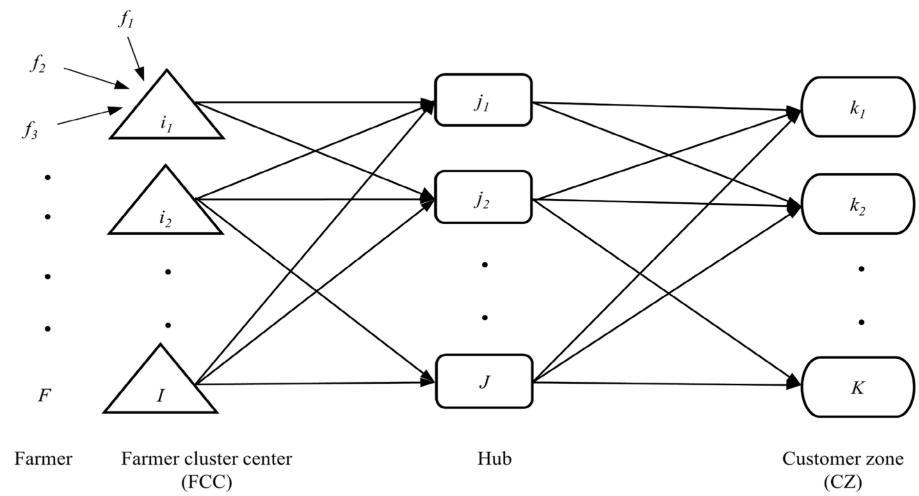
In traditional Indian AFSC, the small farmers bring their products individually to markets (hubs) to sell. It is inefficient as well as an ineffective way of product transportation from farmers to hubs. Authors propose the idea of aggregate product transportation by identifying groups of farmers based on the location of neighborhood farmers. Farmers belonging to a group called as farmer cluster (FC), bring their products to the central location of that cluster which is named as farmers' cluster center (FCC). The central location within a group is considered as any location of a farmer in the group. In this way, multiple FCs and the respective FCCs can be identified. Each farmer can be assigned to only one FCC in each period; therefore, a farmer's supply cannot split into FCCs. On the other side, FCC can split their delivery to any hub. The aggregated products at these FCCs can now be shipped efficiently to the hubs. The lower bound on supply from an FCC to hubs are considered to ensure a minimum quantity of products transported to the lower echelon. It is assumed that FCCs and hubs do not store any items and are used to manage the transshipment of products in SCN to satisfy CZ demand economically. A CZ can receive a split supply from any hub. Similarly, the lower bound on supply from a hub to CZs is considered to ensure a minimum quantity of product movement from a hub.

The aggregate product transportation helps in hassle-free products movement as well as it reduces transportation cost in the delivery of fresh items. Further, it helps in handling various operational issues like easy material handling, proper utilization of facilities, integration of supply, and demand of products. Other issues like carbon emissions, traffic congestion, can be reduced by aggregate transportation. Hence, it is an eco-friendly way of product movement. Also, we consider the perishable nature of products in the modeling of SCN. The excess products are stored in CZs and are used in the next period. The workable inventory and to be expired products are calculated based on the fixed shelf of products; therefore, a suitable inventory flow equation is developed for each CZ. This helps in the reduction of food wastage by determining these excess (to be expired) products which can be supplied to nearby institutional demand nodes like hotel, restaurant, hospital, and hostel.

In traditional Indian AFSC, an agent auctions and matches supply and demand for a market and plays his monopoly in the pricing of products (Viswanadham et al. 2012). The role of this agent can be substituted with modern technology-enabled 'FCC' in the proposed SCN to make the sustainable SC. The modern technology includes the use of image processing to check quality of product, ICT to share information between the partners and radio-frequency identification (RFID) tag to recognize and track the products, etc. which make the whole system dynamic and adaptable for changing scenario (Rais and Sheoran 2015; Dandage et al. 2017; Gokarn and Kuthambalayan 2017; Patidar et al. 2018ba).

The four-echelon location–allocation model consists of farmers, FCCs, hubs, and CZs, as shown in Fig. 2. A mathematical model is formulated by considering single-mode transportation, multi-period, multi-product, and perishability of products in this section. In the model, we first define FCs and the locations of the respective FCCs based on the distance between farmers. All assigned farmers in each FC bring their products to the common collection points, i.e., FCCs. Further, these aggregated products are shipped from FCCs to hubs and hubs to CZs to satisfy demand at CZs such that total SC cost is minimized.

Fig. 2 The proposed SCN model for Indian AFSC



The proposed mixed-integer nonlinear programming (MINLP) formulation of restructured SCN determines the following decisions in each period:

- The appropriate number of FCCs and their locations for the aggregation of products.
- The location and allocation of each hub from the available potential locations to satisfy demand at CZs.
- The quantity of each type of product flow between any two nodes at different echelons.
- The inventory of products at each CZ.
- The to be expired products in each period at each CZ.

Assumptions

The SCN model is formulated using the following assumptions:

1. The model parameters are fixed, and thus, the model is deterministic.
2. The model is multi-period; therefore, excess items in the previous period are used in future periods.
3. Inventory at any echelon arrives at the beginning of a period.
4. The length of a period is one day.
5. Product flow between hubs is not considered in the model.

Proposed formulation

The proposed SCN model is formulated as follows:

$$\textit{Minimize}\ Z = Z1 + Z2 + Z3 + Z4 + Z5 + Z6 + Z7 \tag{1}$$

$$Z1 = \sum_{t=1}^{T}\sum_{i=1}^{I} FC1_i F_i^t \tag{1a}$$

$$Z2 = \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{f=1}^{F}\sum_{p=1}^{P} D1_{fi} TC_1 H_{fp}^t Y_{fi}^t \tag{1b}$$

$$Z3 = \sum_{t=1}^{T}\sum_{j=1}^{J} FC2_j Z_j^t \tag{1c}$$

$$Z4 = \sum_{t=1}^{T}\sum_{i=1}^{I}\sum_{j=1}^{J}\sum_{p=1}^{P} D2_{ij} TC_2 Q_{ijp}^t \tag{1d}$$

$$Z5 = \sum_{t=1}^{T}\sum_{j=1}^{J}\sum_{k=1}^{K}\sum_{p=1}^{P}\sum_{\tau\geq t}^{T} D3_{jk} TC_3 Q_{jkp}^{t\tau} \tag{1e}$$

$$Z6 = \sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{p=1}^{P} HC_{kp} I_{kp}^t \tag{1f}$$

$$Z7 = \sum_{t=1}^{T}\sum_{k=1}^{K}\sum_{p=1}^{P} DC_p Ex_{kp}^t. \tag{1 g}$$

The objective function (1) minimizes the total cost (TC) occurring at various stages of the SC. TC includes four types of costs, i.e., fixed costs, transportation costs, inventory holding cost, and disposal cost of expired products at CZs. The explanation of these costs is as follows. Equations (1a) and (1c) denote fixed costs of forming FCCs and opening hubs, respectively. Equations (1b), (1d), and (1e) describe transportation costs from farmers to FCCs, FCCs to hubs, and hubs to CZs, respectively. Lastly, Eqs. (1f) and (1g) represent total inventory holding cost and disposal cost for the expired products at CZs, respectively.

Subject to:

$$D1_{fi}Y_{fi}^{t} \leq D1_{m}, \quad \forall f, \forall i, \forall t \tag{2}$$

$$\sum_{i=1}^{I} Y_{fi}^{t} F_{i}^{t} = 1, \quad \forall f, \forall t. \tag{3}$$

Equations (2) and (3) define the FCs by identifying the associated farmers, and the respective FCCs based on allowed maximum distance traveled by a farmer.

$$\sum_{f=1}^{F} H_{fp}^{t} Y_{fi}^{t} \leq M \times F_{i}^{t}, \quad \forall i, \forall p, \forall t \tag{4}$$

$$\sum_{j=1}^{J} Q_{ijp}^{t} = \sum_{f=1}^{F} H_{fp}^{t} Y_{fi}^{t}, \quad \forall i, \forall p, \forall t. \tag{5}$$

Equation (4) ensures the movement of products from farmers to the established FCCs only. Equation (5) ensures the sum of products shipped from each FCC to any hub is equal to the available aggregate product of each type during each period.

$$\sum_{j=1}^{J} Q_{ijp}^{t} \geq LB_{ip} F_{i}^{t}, \quad \forall i, \forall p, \forall t \tag{6}$$

$$\sum_{i=1}^{I} Q_{ijp}^{t} \leq M \times Z_{j}^{t}, \quad \forall j, \forall p, \forall t. \tag{7}$$

The lower bound on supply from each FCC to any hub is ensured by Eq. (6). Equation (7) ensures shipment of product from FCCs to the opened hubs only.

$$\sum_{k=1}^{K} \sum_{\tau \geq t}^{T} Q_{jkp}^{\prime t\tau} = \sum_{i=1}^{I} Q_{ijp}^{t}, \quad \forall j, \forall p, \forall t \tag{8}$$

$$\sum_{j=1}^{J} \sum_{t-lp \leq \tau \leq t}^{T} Q_{jkp}^{\prime \tau t} \geq D_{kp}^{t}, \quad \forall k, \forall p, \forall t. \tag{9}$$

Conservation of products' flow at each hub for each period is governed by Eq. (8). Equation (9) guarantees that the quantity of delivered products to each CZ is greater than or equal to the demand during each period.

$$I_{kp}^{t-1} + \sum_{j=1}^{J} \sum_{\tau \geq t}^{T} Q_{jkp}^{\prime t\tau} - D_{kp}^{t} - Ex_{kp}^{t} = I_{kp}^{t}, \quad \forall k, \forall p, \forall t \tag{10}$$

$$\sum_{j=1}^{J} \sum_{\tau > t+l_p}^{T} Q_{jkp}^{\prime t\tau} = Ex_{kp}^{t}, \quad \forall k, \forall p, \forall t. \tag{11}$$

Inventory flow balance is governed by Eq. (10) for two consecutive periods at each CZ. Equation (11) determines the to be expired products for each product type in every period at each CZ based on the pre-defined shelf life of each product type.

$$\sum_{k=1}^{K} \sum_{\tau \geq t}^{T} Q_{jkp}^{\prime t\tau} \geq LB_{jp} Z_{j}^{t}, \quad \forall j, \forall p, \forall t. \tag{12}$$

The lower bound on supply from each opened hub to any CZ is warranted by Eq. (12).

$$\sum_{j=1}^{J} Z_{j}^{t} = NH, \quad \forall t. \tag{13}$$

Equation (13) ensures the total number of hubs to be opened in each period.

$$F_{i}^{t}, Z_{j}^{t}, Y_{fi}^{t} = \{0, 1\}. \tag{14}$$

The binary variables are ensured by Eq. (14).

Model implementation and numerical results

In this section, a case study of AFSC ofMadhya Pradesh (a central province of India) has been considered to implement the proposed model. Madhya Pradesh is agriculturally productive and has won five successive the 'Krishi Karman Award' for the huge agriculture production in the financial year 2012–13 to 2016–17 (The Times of India 2018). As reported in "High wastage of agricultural products" section, a large amount of agricultural products is being wasted due to poor logistics management. This wastage leads to environmental pollution in terms of both bad air quality and development of bacteria, especially near the Mandis and warehouses. Additionally, the unorganized SC structure and inefficient transportation of products leads to the low profitability of farmers. The proposed model has been framed to organize and mitigate the actual shortcomings by incorporating the perishability of products and clustering of farmers. Further, the case study problem aims to implement our proposed model by dealing with actual circumstances. The complete illustration of data collection, optimal results, SC dynamics, and sensitivity analysis for the case study problem are explained in "Data collection" to "Sensitivity analysis" section, respectively.

Table 1 Group of vegetables

Product type	Name of vegetables	Shelf life (in days)
P1	Coriander, spinach	1
P2	Brinjal, chili, capsicum, bitter, cauliflower, beans, carrot, bottle gourd, cucumber, lady's finger, pointed gourd, radish	2
P3	Tomato, cabbage	3
P4	Potato, onion, pumpkin.	6

Table 2 Estimated value of parameters in kg

Product type	Farmer supply capacities	CZ demand quantities	Lower bound on supply from an FCC	Lower bound on supply from a hub
P1	5–20	18–30	5	30
P2	40–75	100–160	30	100
P3	25–50	80–100	20	80
P4	110–150	230–330	100	200

Data collection

The farmers (supply nodes) and customers (demand nodes) in Mandsaur District of Madhya Pradesh province are chosen as candidate locations for the vegetable SC. The common vegetables which are generally produced by farmers (MoAFW 2017) and consumed by customers (NSSO 2014) for the district are identified. These common vegetables are assumed and classified into four groups based on the shelf life of products. These groups of vegetables are mentioned as product types in the model and are described in Table 1.

Farmers from the villages and customers from highly populated zones (in a city) supply and demand the vegetables, respectively. In this work, it is assumed that each village as a farmer unit and its location as a farmer's location. The case study assumes fifty available farmers' locations (F1–F50), which supply four types of vegetables (P1–P4). A total of twenty wards of Mandsaur City are considered as CZs' locations (C1–C20). A set of seven locations (H1–H7) in the city area is defined as hubs' locations for the re-distribution of products from farmers/FCCs to CZs. Farmer's vegetable production is estimated using the data of per hectare vegetable yield (MoAFW 2017) and average landholding of each farmer (Census of India 2011). Similarly,consumption in each CZ is estimated using the data of consumption of vegetables per person/day (NSSO 2014) and thepopulation of each CZ (Census of India 2011). Based on these data, the average supply and demand of vegetables are calculated for all farmer units and CZs. The minimum and maximum farmers' supply capacities, as well as minimum and maximum CZs' demand quantities for a single period, are presented in Table 2. Further, these single period estimates of supply and demand are used to generate supply and demand for ten periods (T1–T10) with the help of probabilistic uniform distribution function. The values of lower bound on supply from an FCC and a hub for the estimated data for different product types are shown in Table 2. The fixed cost, transportation cost, holding cost, and disposal cost for the problem are assumed based on our experience and prevailing conditions of Mandsaur District as presented in Table 3. Further, the distance between farmers, farmers/FCCs to hubs, and hubs to CZs are obtained from google maps (Google Maps 2018). Figure 3 shows the locations of farmers, hubs, and CZs for the case study problem.

Table 3 Value of various cost parameters

Parameter	Value (INR)
(1) Fixed cost of each facility for each period	
FCC	500
Hub	5000
(2) *Transportation cost (per kg/km)*	
From farmer to FCC	1
From FCC to hub	1
From hub to CZ	1
(3) Holding cost for each CZ (per kg/period)	
P1	5
P2	3
P3	2
P4	2
(4) Disposal cost of per kg expired product at each CZ	
P1, P2, P3, and P4	1

Optimal results

The proposed MINLP model is coded and solved using LINGO 17.0 optimization package with a PC having

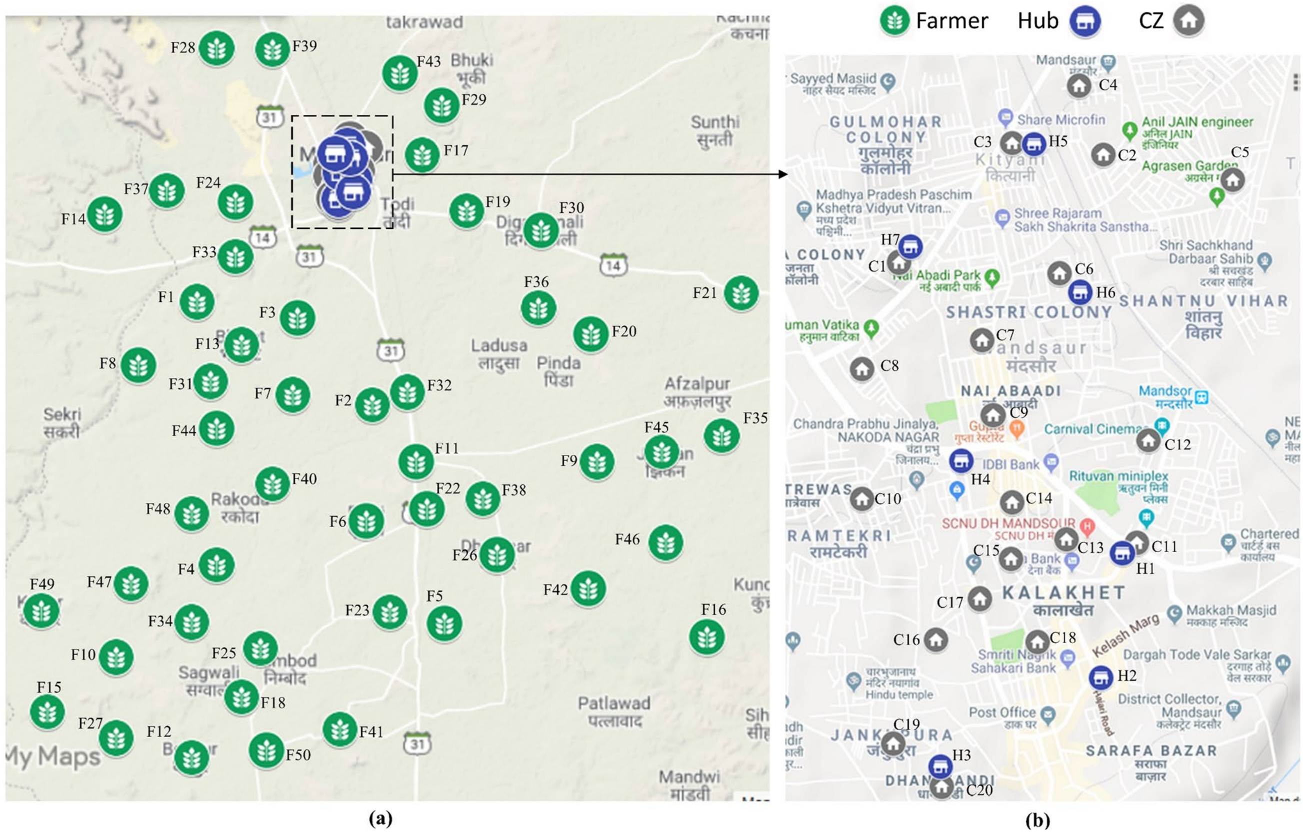


Fig. 3 **a** Locations of farmers, hubs, and CZs of Mandsaur region for case study problem; **b** locations of hubs and CZs in the zoomed figure

Windows 10 operating system, Intel Core i5 processor, and 8 GB of RAM configuration. The MINLP model is solved for the case study problem by referring the data from Tables 1, 2, and 3. The problem has a total 34,519 constraints, 500 nonlinear constraints, 97,438 variables, and 25,500 integer variables.

The formation of FCs is based on quantities supply by farmers and allowed maximum distance traveled by a farmer for belonging to an FCC. Similarly, decisions regarding the opening of hubs depend on supply and demand, and the distances between any two nodes of consecutive echelons. To find the best result, 16 experiments by changing the number of hubs to be opened and the maximum distance traveled by a farmer are conducted. The results of these experiments are shown in Table 4. It is reported that the experiment (A4), which has 4 number of hubs and 18 km distance traveled by a farmer, gives the best result (minimum TC). The solver reports an optimal cost of INR 2.794×10^6 by solving the proposed MINLP model in 17 min and 29 s. The best result reports that in order to meet the supply and demand of the defined problem, FCCs between 15 and 18 are formed in different periods for the aggregation of the products out of 50 farmers. All costs incurred in the proposed SCN model are shown in Table 4. Figure 4 shows the locations of farmers, FCCs, CZs, and hubs for period 1.

The percentage of various costs incurred for the experiment A4 (best result) is shown in Fig. 5. One important observation that can be noted from the figure is that the sum of the percentage contribution of costs Z2 and Z4 is 85% of the total SC cost. This suggests to reduce these two costs. The cost Z2 can be reduced by decreasing the distance traveled by farmers to FCCs. This, in turn, increases the number of FCs/FCCs, which will increase the cost of product transportation from FCCs to hubs. Hence, the major focus should be to design a transportation model for the transportation of agriculture products from FCCs to hubs in an efficient manner for minimization of Z4.

SC dynamics

As discussed in "Model description" section, the proposed model has been developed to address the realistic problems of the Indian AFSC. The dynamics of the SC for the case study problem has been presented to show the model capabilities for the best scenario (experiment A4, Table 4). The inputs (supply and demand data) and outputs (quantities of product shipped and inventory) for this experiment

Table 4 Computational results for the case study problem

Experiment	Number of hubs to beopened (*NH*)	Maximum distance traveled by a farmer ($D1_m$)	Range of FCCs formed in each period	Fixed cost of forming FCCs (Z1)	Transportation cost from farmers to FCCs (Z2)	Fixed cost of opening hubs (Z3)	Transportation cost from FCCs to hubs (Z4)	Transportation cost from hubs to CZs (Z5)	Inventory holding cost at CZs (Z6)	Disposal cost of expired products at CZs (Z7)	Total Cost (TC)	Computational time (mm:ss)
A1	4	9	20–23	109,000	379,626	200,000	2,036,620	81,520	47,274	7518	2,861,559	17:08
A2		12	17–19	90,500	528,154	200,000	1,869,354	81,190	47,354	7518	2,824,070	17:08
A3		15	15–18	82,000	634,044	200,000	1,751,964	81,172	47,354	7518	2,804,053	29:50
A4		18	15–18	78,500	694,860	200,000	1,684,781	81,173	47,354	7518	2,794,187[a]	17:29
B1	5	9	20–23	108,000	382,868	250,000	2,037,007	75,956	47,354	7518	2,908,703	21:48
B2		12	17–19	90,500	526,650	250,000	1,867,506	80,953	47,354	7518	2,870,481	11:08
B3		15	15–18	81,500	637,668	250,000	1,749,403	77,312	47,354	7518	2,850,756	53:03
B4		18	13–18	78,000	692,094	250,000	1,688,573	77,311	47,354	7518	2,840,851	23:44
C1	6	9	20–23	108,500	380,662	300,000	2,038,603	74,367	47,234	7518	2,956,885	07:10
C2		12	17–19	90,500	525,479	300,000	1,873,191	74,064	47,354	7518	2,918,108	06:25
C3		15	15–18	81,000	638,819	300,000	1,750,977	73,342	47,244	7518	2,898,901	10:26
C4		18	14–18	78,000	697,028	300,000	1,686,829	72,469	47,244	7518	2,889,098	11:52
D1	7	9	20–23	109,000	379,616	350,000	2,044,634	68,271	47,154	7518	3,006,194	04:33
D2		12	17–19	90,500	526,005	350,000	1,877,755	68,242	47,154	7518	2,967,175	02:48
D3		15	15–18	81,500	638,545	350,000	1,755,422	68,269	47,164	7518	2,948,419	01:17
D4		18	14–18	78,500	696,754	350,000	1,690,340	68,243	47,154	7518	2,938,510	01:19

[a]Best result

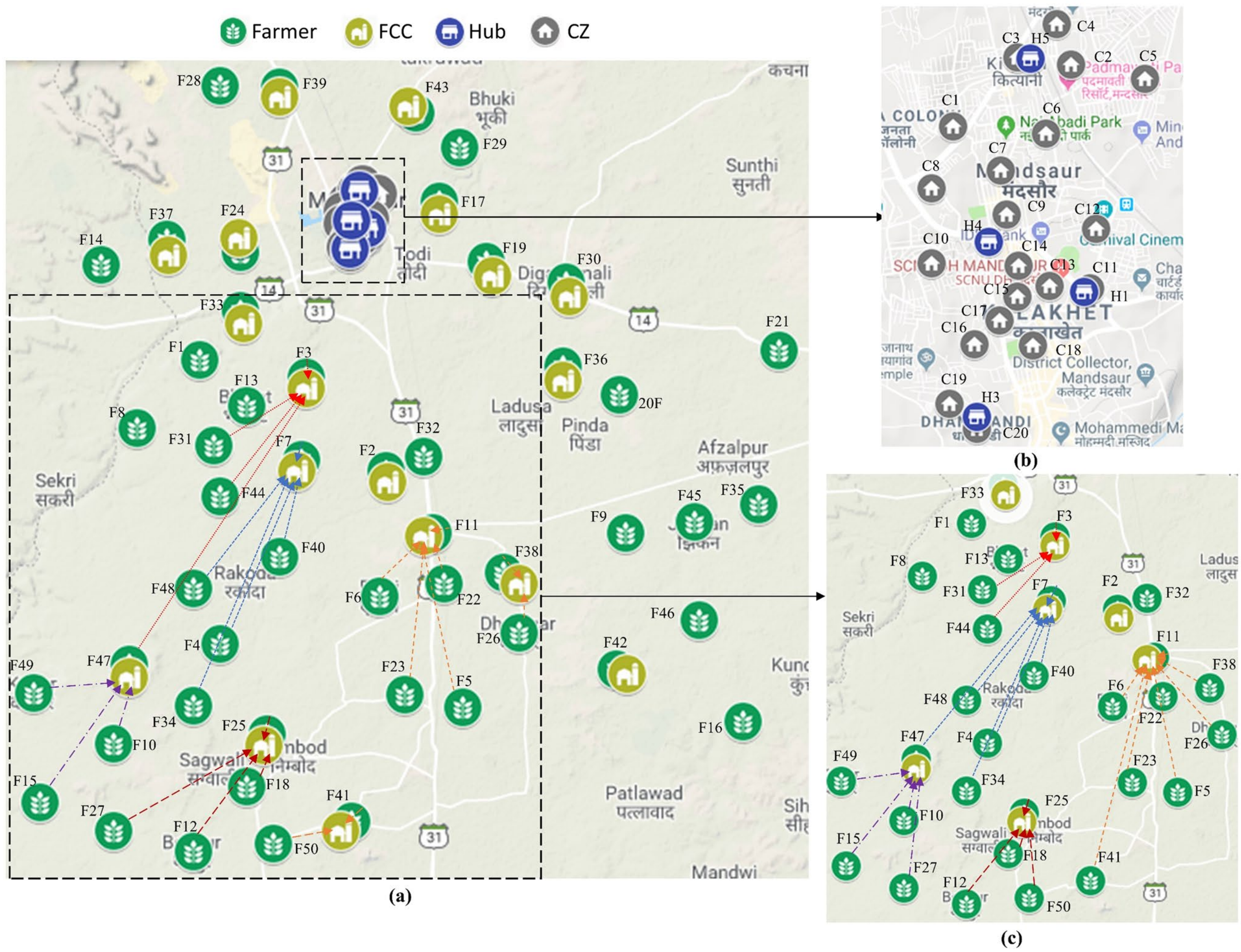


Fig. 4 **a** Locations of farmers, FCCs, hubs, and CZs of Mandsaur region based on the proposed SCN model for T1; **b** locations of hubs and CZs in the zoomed figure for T1; (c) locations of farmers and FCCs of the dotted rectangle for T2

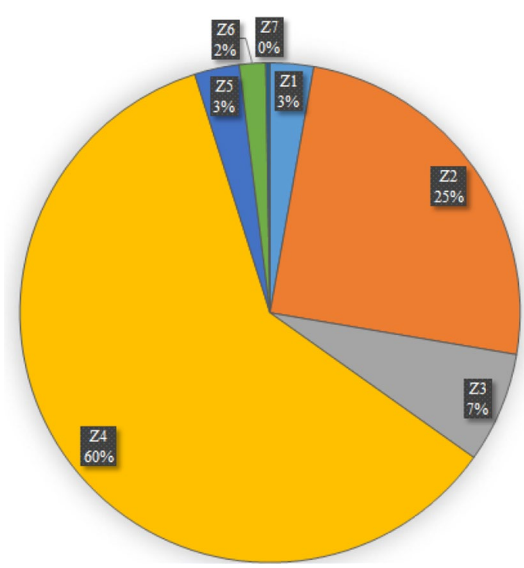


Fig. 5 The percentage of costs incurred in the proposed SCN model

are presented for time periods T1 and T2 in 'Appendix' (Tables 8–12). The quantities of products P1 and P3 shipped in periods T1 and T2 from farmers to CZs through FCCs and hubs are presented in Table 5 (cases I–IV) and Tables 6 and 7 (cases V–VIII) for H4 and H3, respectively. The dynamics of the SC is analyzed by mainly emphasizing on the formation of the cluster, allocation of FCCs to hubs, inventory dynamics in terms of quantities held and to be expired products. Various observations and corresponding explanations in terms of the formation of FCCs, and distribution of products (based on the supply/demand in a period) with the main objective of distance minimization are given as follows.

(1) It is observed that many times an FCC is supplying to the multiple hubs, for example, cases II and III for products P3 and P1, respectively. In case II, FCC F3 supplies 16 units of product to hub H4 to satisfy its demand, and the remaining 117 units are supplied to

Table 5 Supply chain dynamics in periods T1 and T2 for products P1 and P3 at hub H4

Case I: For product P1 in period T1						Case II: For product P3 in period T1					
Farmers belonging to an FCC with available supply	Aggregate quantity at FCC	Quantity shipped from FCC to the hub	Total quantity received at H4 from FCCs	Quantity shipped from hub to CZ	Demand at CZ	Farmers belonging to an FCC with available supply	Aggregate quantity at FCC	Quantity shipped from FCC to the hub	Total quantity received at H4 from FCCs	Quantity shipped from hub to CZ	Demand at CZ
F3 (15[a])	F3 (52)	**H3 (24)** H4 (28)	H4 (75)	C1 (29) C8 (23) C10 (23)	C1 (29) C8 (23) C10 (23)	F3 (29)	F3 (133)	**H3 (117)** H4 (16)	H4 (274)	C1 (85 + 13) C8 (85) C10 (91)	C1 (85) C8 (85) C10 (91)
F31 (11)						F31 (40)					
F44 (13)						F44 (38)					
F47 (13)						F47 (26)					
F24 (12)	F24 (12)	H4 (12)				F24 (43)	F24 (43)	H4 (43)			
F1 (14)	**F33 (50)**	**H3 (50)**				F1 (27)	F33 (143)	H4 (143)			
F8 (5)						F8 (49)					
F13 (16)						F13 (33)					
F33 (15)						F33 (34)					
F14 (16)	F37 (35)	H4 (35)				F14 (29)	F37 (75)	H4 (72) **H5 (3)**			
F37 (19)						F37 (46)					
Total quantity shipped from H4 to CZs is same as quantity demanded at CZs						Quantity shipped from H4 to C1 is more by 13 units and will be used in next periods					
Case III: For product P1 in period T2						Case IV: For product P3 in period T2					
F3 (11)	**F3 (35)**	**H3 (35)**	H4 (74)	C1 (22) C8 (29) C10 (23)	C1 (22) C8 (29) C10 (23)	F3 (44)	F3 (143)	**H3 (124)** H4 (19)	H4 (255)	C1 (70) C8 (97) C10 (88)	C1 (70) C8 (97) C10 (88)
F31 (9)						F31 (50)					
F44 (15)						F44 (49)					
F24 (5)	F24 (5)	H4 (5)				F24 (35)	F24 (35)	H4 (35)			
F1 (14)	F33 (44)	**H3 (1)** H4 (43)				F1 (37)	F33 (148)	H4 (148)			
F8 (17)						F8 (36)					
F13 (8)						F13 (33)					
F33 (5)						F33 (42)					
F14 (20)	F37 (30)	H4(26) **H5 (4)**				F14 (38)	F37 (68)	H4 (53) **H5 (15)**			
F37 (10)						F37 (30)					
Total quantity shipped from H4 to CZs is same as quantity demanded at CZs						Total quantity shipped from H4 to CZs is same as quantity demanded at CZs					

[a]Number in bracket represents quantity of product

Table 6 Supply chain dynamics in period T1 for product P1 and P3 at hub H3

Case V: For product P1 in period T1						Case VI: For product P3 in period T1					
Farmers belonging to an FCC with available supply	Aggregate quantity at FCC	Quantity shipped from FCC to the hub	Total quantity received at H3 from FCCs	Quantity shipped from hub to CZ	Demand at CZ	Farmers belonging to an FCC with available supply	Aggregate quantity at FCC	Quantity shipped from FCC to the hub	Total quantity received at H3 from FCCs	Quantity shipped from hub to CZ	Demand at CZ
F2 (8)	F2 (17)	H3 (17)	H3 (293)	C16 (25) C17 (24) C19 (19) C20 (19 + 206)	C16 (25) C17 (24) C19 (19) C20 (19)	F2 (32)	F2 (68)	H3 (1) **H4 (67)**	H3 (407)	C16 (93) C17 (82) C19 (89) C20 (85 + 58)	C16 (93) C17 (82) C19 (89) C20 (85)
F32 (9)						F32 (36)					
F3 (15)	F3 (52)	H3 (24) **H4 (28)**				F3 (29)	F3 (133)	H3 (117) **H4 (16)**			
F31 (11)						F31 (40)					
F44 (13)						F44 (38)					
F47 (13)						F47 (26)					
F4 (14)	F7 (73)	H3 (73)				F4 (29)	F7 (189)	H3 (189)			
F7 (18)						F7 (36)					
F34 (11)						F34 (45)					
F40 (14)						F40 (36)					
F48 (16)						F48 (43)					
F12 (19)	F25 (54)	**H1 (11)** H3 (43)				**F12 (31)**	**F25 (131)**	**H1 (131)**			
F18 (5)						**F18 (44)**					
F25 (15)						**F25 (25)**					
F27 (15)						**F27 (31)**					
F1 (14)	F33 (50)	H3 (50)				**F1 (27)**	**F33 (143)**	**H4 (143)**			
F8 (5)						**F8 (49)**					
F13 (16)						**F13 (33)**					
F33 (15)						**F33 (34)**					
F26 (17)	F38 (30)	H3 (30)				**F26 (31)**	**F38 (69)**	**H1 (69)**			
F38 (13)						**F38 (38)**					
F41 (11)	F41 (21)	H3 (21)				**F41 (33)**	**F41 (81)**	**H1 (81)**			
F50 (10)						**F50 (48)**					
F10 (12)	F47 (35)	H3 (35)				F10 (36)	F47 (100)	H3 (100)			
F15 (9)						F15 (38)					
F49 (14)						F49 (26)					
Quantity shipped from H3 to C20 is more by 206 units will be expired after one time period						Quantity shipped from H3 to C20 is more by 58 units will be expired after three time periods					

Table 7 Supply chain dynamics in period T2 for product P1 and P3 at hub H3

Case VII: For product P1 in period T2						Case VIII: For product P3 in period T2					
Farmers belonging to an FCC with available supply	Aggregate quantity at FCC	Quantity shipped from FCC to the hub	Total quantity received at H3 from FCCs	Quantity shipped from hub to CZ	Demand at CZ	Farmers belonging to an FCC with available supply	Aggregate quantity at FCC	Quantity shipped from FCC to the hub	Total quantity received at H3 from FCCs	Quantity shipped from hub to CZ	Demand at CZ
F2 (5)	**F2 (21)**	**H1 (21)**	H3 (220)	C16 (20) C17 (21) C19 (24) C20 (23 + 132)	C16 (20) C17 (21) C19 (24) C20 (23)	**F2 (41)**	**F2 (69)**	**H1 (69)**	H3 (388)	C16 (99) C17 (100) C19 (90) C20 (99)	C16 (99) C17 (100) C19 (90) C20 (99)
F32 (16)						**F32 (28)**					
F3 (11)	F3 (35)	H3 (35)				F3 (44)	F3 (143)	H3 (124) **H4 (19)**			
F31(9)						F31 (50)					
F44 (15)						F44 (49)					
F4 (13)	F7 (73)	**H1 (38)** H3 (35)				**F4 (25)**	**F7 (194)**	**H1 (194)**			
F7 (8)						**F7 (25)**					
F34 (14)						**F34 (26)**					
F40 (12)						**F40 (39)**					
F47 (13)						**F47 (43)**					
F48 (13)						**F48 (36)**					
F12 (16)	**F25 (52)**	**H1 (52)**				F12 (38)	F25 (145)	**H1 (47)** H3 (98)			
F18 (10)						F18 (35)					
F25 (20)						F25 (45)					
F50 (6)						**F50 (27)**					
F1 (14)	F33 (44)	H3 (1) **H4 (43)**				F1 (37)	**F33 (148)**	**H4 (148)**			
F8 (17)						F8 (36)					
F13 (8)						F13 (33)					
F33 (5)						F33 (42)					
F5 (11)	F11 (104)	H3 (104)				**F5 (27)**	F11 (302)	**H1 (302)**			
F6 (13)						**F6 (50)**					
F11 (12)						**F11 (27)**					
F22 (9)						**F22 (38)**					
F23 (19)						**F23 (41)**					
F26 (16)						F26 (41)					
F38 (13)						F38 (34)					
F41 (11)						F41 (44)					
F10 (6)	F47 (45)	H3 (45)				F10 (27)	F47 (166)	H3 (166)			
F15 (19)						F15 (48)					
F27 (13)						**F27 (50)**					
F49 (7)						F49 (41)					
Quantity shipped from H3 to C20 is more by 132 units will be expired after one time period						Total Quantity shipped from H3 to CZs is same as quantity demanded at CZs					

hub H3 because H3 is near with respect to H4 (Fig. 3). Similarly, FCC F37 for cases II and III supplies the needed quantities of the product at hub H5 and the remaining units of product are supplied to hub H4 because H4 is near concerning H5.

(2) Another observation is that the formation of clusters in a time period is the same for all products. For example, compare cases I and II for FCC at F33. When we look for product P1 (case I) and P3 (case II) in period T1, FCC 33 has been re-allocated from H3 to H4 to fulfill the higher demand of product P3 at H4. In the proposed model, the formation of FCs and respective FCCs in a period for different products remains the same, which allows the farmers to transport all the products to the single FCC. It means there is no split supply from farmers to FCC. Although the supply from FCC to the hub(s) can be split based on the demand at CZs. A similar observation can be noted in period T2.

(3) Another observation is that the model tries to modify an FC—formed in the previous period —by merging with or breaking existing cluster(s) to satisfy the demand at CZs based on available supply in a period. For example, the demand for product P1 at H1 (Table 11) has increased by 24 units from period T1 to T2. In order to satisfy the increased demand in T2, the FCCs F2, F7, and F25 supply to H1 as well as farmer F50 merge in FCC at F25 (case VII). On the side, FCC F11 enlarges by merging farmer F26, F38, and F41 which supply to H3. The merging of FCC F26 and F41 in F11 reduces the formation cost of FCCs.

(4) Further, the results of the model maintain cluster formation nearly the same in different periods (compare case I/II with case III/IV). The model tries to maintain consistency in the assignment of farmers to an FCC and an FCC to the hub(s) for the distribution of products in different periods.

(5) The model determines the excess inventory at the end of a period, which is to be used in the next period(s), and to be expired inventory based on supply/demand, planning horizon, and shelf life of products. In case II, the total demand at CZs C1, C8, and C10 is 261 units, whereas 274 units are shipped from hub H4 to CZs. The excess 13 units at C1 will be used in the next period(s) (Table 12). On the other hand, in case V, the total demand at CZs C16, C17, C19, and C20 is 87 units only, whereas 293 units are supplied from hub H3 to these CZs. The excess 206 units supplied at C20 are the to be expired inventory at the end of the period (since the shelf life of P1 is one period). Hence, the model is capable of determining the to be expired products in advance, which can be supplied to other institutional demand locations/nodes.

(6) It is observed that a greater number of farmers and FCCs are allocated to hub H3 because H3 is near the most of farmers in comparison with H4 (refer Fig. 3 and Tables 5, 6, 7). Also, the excess products from hub H3 are supplied to CZ C20, which is closest in comparison with other CZs. For example, the difference between the total supply and demand of product P1 in period T1 through all hubs (Tables 10 and 11) is higher in comparison with P3; therefore, the excess production of P1 is supplied to H3 (case V).

Sensitivity analysis

Sensitivity Analysis is a tool used in mathematical modeling to analyze how the different values of an independent variable affect dependent variables. The analysis is performed to check the effects of the maximum distance traveled by a farmer ($D1_m$) to reach an FCC and number of hubs to be opened (*NH*) on the various costs. The following observations are reported in Table 4. The first outcome is reported by viewing the results of the experiments from A1 to A4. Increasing maximum distance traveled by a farmer (with a fixed value of number of hubs) increases the size of an FC (a greater number of farmers can access an FCC) and reduces the number of FCCs which in turn minimizes cost Z1. Further, reducing the number of FCCs results in decreased transportation cost from FCCs to hubs (Z4) since the total distance traveled from all FCCs to hubs is decreased. On the other side, transportation cost from farmers to FCCs (Z2) is increased due to increasing distance traveled by farmers. However, the cost Z3 observes no effect, and Z5 reports insignificant variation within the same set of experiments. Finally, the overall effect of changing maximum distance traveled by a farmer on the TC is very small. Similar patterns in costs variations are also reported in the sets of experiments B1–B4, C1–C4, and D1–D4.

The second outcome is reported by analyzing experiments A1, B1, C1, and D1. By increasing the value of the number of hubs to be opened (with a constant value of maximum distance traveled by a farmer), the cost required of opening hubs (Z3) increases because each hub is associated with some fixed opening cost. On the other side, transportation cost from FCCs to hubs (Z4) is observed with no trivial variations because of the potential locations of all hubs are nearer with respect to the distances from farmers, whereas transportation cost from hubs to CZs (Z5) is reduced due to the locations of new opening hubs dispersed in the city area which minimizes the total distance traveled from hubs to CZs (Fig. 3b). There is no effect of changing the value of number of hubs on the fixed cost of forming FCCs (Z1). In this way, the TC increases with respect to increasing the value of number of hubs. Similar patterns in the results are also found for the experiments A2, B2, C2, D2 and A3, B3, C3, D3 and A4, B4, C4, D4 in Table 4.

The third observation is that there is no effect of changing maximum distance traveled by a farmer and number of hubs to be opened on the inventory costs Z6 and Z7 (almost constant) in all the experiments (A1–D4), because these costs mainly depend on supply and demand, which are considered the same for all the experiments. Hence, it is concluded that our model is robust with respect to changes in the maximum distance traveled by a farmer to reach a farmer cluster center. On the other hand, the model is sensitive with respect to changes in the number of hubs to be opened.

Concluding remarks and future work

Out of the four major problems which are identified in this research work, one of the shortcomings improper structure of traditional Indian AFSC results in the other two shortcomings—low profitability of farmers and high wastage of agriculture products. From small-farm-holding farmers (which is a shortcoming), the inefficient transportation of products to market is the another (major) cause of the farmers' low profitability. In this work, authors suggest the clustering of farmers for the integration of small farmers' supply at the cluster centers and transportation of these aggregated products to the hubs. The idea of aggregate product shipment reduces the transportation cost from farmers to hubs. Further, the perishable nature of products in the modeling of the distribution network is considered to reduce food wastage in the chain.

A four-echelon, multi-period, multi-product SCN model for Indian AFSC is developed by considering the clustering of farmers and perishability of products. The model aims to minimize the total distribution cost which comprises the fixed cost of opening facilities, transportation costs from farmers to CZs, inventory holding cost and disposal cost of expired products at CZs. The developed model determines the required number of FCCs for aggregation of products, allocation of facilities (FCCs and hubs), quantities of products flow between the facilities as well as inventory and the to be expired products at each CZ. To implement the model, a case study problem of Mandsaur District (India) is considered for the distribution of vegetables. Sensitivity analysis shows that the proposed model is robust and sensitive with respect to changes in the maximum distance traveled by a farmer to reach a cluster center and the number of hubs to be opened, respectively.

The model has been proposed in order to solve the identified shortcomings in the following ways: The organized SC is well planned to reach the consumers. It governs and controls all the activities of the SC. Hence, we have developed an SC model to organize the Indian AFSC. The effects of small-farm-holding farmers are mitigated by considering aggregation of products using clustering of farmers. The transportation of aggregate products reduces transportation cost from farmers to hubs which will be benefited to the farmers. The proposed formulation also includes the perishable nature of products which determines excess products in advance. These excess products can be supplied to other institutional demand nodes (like hospitals, hostels, and restaurants); thus, it will reduce the wastage of agricultural products.

In the article, authors addressed three dimensions of sustainability: economical (minimization of transportation cost), social (enhancement of farmers' profitability), and environmental dimension (reduction of agricultural wastage and carbon emissions). The SC dynamics shows that the proposed model is capable to include the supply and demand variability in determining the optimal location–allocation of FCCs and hubs. The proposed SCN model may help the existing agricultural retail chains (like Reliance Fresh, Big Bazar, Big-basket) in the collection of items from the small farmers.

Managerial insights

Based on the results of the study, the following managerial insights can be noted. In traditional SC, farmers individually bring their products from the farming locations to the hubs. The TC of product movement is borne by the farmers, and it is mainly responsible for the low profitability of the farmers, as reported in "Low profitability of farmers" section. In this work, authors recommend that farmers should aggregate their products at an optimal cluster center then, transport these products from an FCC to the hub by incorporating an appropriate transportation plan to minimize transportation cost. The outcome of the model further confirms the same which shows that the transportation costs from farmers to FCCs (Z2) and FCCs to hubs (Z4) have 85% contribution to the total SC cost (Fig. 5). The results of the sensitivity analysis report that the minimum number of hubs to be opened (transshipment nodes) gives the best result of the model. The developed model guides managers and policymakers to identify the optimal location of facilities (FCCs and hubs) where suitable infrastructure can be developed. The aggregate transportation of products will reduce carbon emissions and traffic congestion; hence, it is an eco-friendly strategy for product transportation. Further, the proposed formulation can be applied for other products' SC with considering shelf life of the products (Gholamian and Taghanzadeh 2017).

Future work

This paper has proposed a mathematical model to redesign the traditional Indian AFSC. It is obvious that the formulated mathematical model is not applicable without addressing other aspects of the SC. Although the proposed model is practical, there are two main limitations that need to be improved in future studies: first, the conceptual framework and policies to handle various operational issues like pricing, packaging and coordination and cooperation amongst the SC actors, and Second, the information technology model (app/website) to maintain the dynamic relationship between players for the proposed SCN model. Additionally, a suitable vehicle routing model can be included to reduce further the transportation cost from FCCs to the hub(s). Also, metaheuristic solution approaches can be used to study computational complexity for large data set problems. The concept of reverse logistics, as suggested by Bottani et al. (2019), can be incorporated to move the waste products and packaging materials from hubs to farmers/FCC locations, where it can be recycled (to make compost) (Waqas et al. 2018) and reused, respectively.

Appendix

See Tables 8, 9, 10, 11, and 12.

Table 8 Farmer supply availability for periods T1 and T2

Farmer	T1 period				T2 period			
	P1	P2	P3	P4	P1	P2	P3	P4
F1	14	66	27	143	14	53	37	120
F2	8	45	32	137	5	53	41	126
F3	15	62	29	124	11	49	44	118
F4	14	68	29	132	13	65	25	136
F5	13	44	30	136	11	56	27	121
F6	16	46	43	143	13	51	50	145
F7	18	50	36	132	8	43	25	115
F8	5	41	49	137	17	59	36	123
F9	19	74	50	129	18	53	47	132
F10	12	74	36	124	6	47	27	130
F11	18	66	36	135	12	70	27	123
F12	19	70	31	119	16	46	38	130
F13	16	55	33	146	8	74	33	148
F14	16	57	29	132	20	74	38	136
F15	9	47	38	150	19	71	48	111
F16	10	61	45	132	14	52	35	134
F17	9	75	45	138	20	62	27	150
F18	5	46	44	133	10	45	35	111
F19	17	68	28	144	19	52	39	149
F20	19	63	41	138	17	49	28	127
F21	18	66	44	139	11	43	50	136
F22	7	48	38	150	9	40	38	146
F23	8	44	41	150	19	62	41	130
F24	12	46	43	143	5	58	35	139
F25	15	44	25	138	20	53	45	129
F26	17	48	31	125	16	62	41	135
F27	15	45	31	123	13	54	50	119
F28	16	72	46	112	5	60	36	134
F29	11	50	43	143	8	57	26	116
F30	16	47	38	137	17	41	38	123
F31	11	44	40	129	9	41	50	148
F32	9	56	36	135	16	49	28	148
F33	15	72	34	120	5	47	42	144
F34	11	66	45	124	14	70	26	132
F35	8	69	41	134	11	71	49	124
F36	10	62	41	111	7	50	30	118
F37	19	59	46	149	10	45	30	129
F38	13	71	38	137	13	68	34	130
F39	18	69	42	131	6	75	45	129
F40	14	50	36	147	12	43	39	129
F41	11	62	33	113	11	54	44	136
F42	13	50	34	115	12	69	44	128
F43	16	75	50	147	6	67	28	124
F44	13	53	38	126	15	57	49	113
F45	20	72	29	148	18	44	29	120
F46	6	63	45	141	7	68	33	142
F47	13	60	26	144	13	56	43	124
F48	16	49	43	130	13	75	36	147
F49	14	42	26	150	7	71	41	144

Table 8 (continued)

Farmer	T1 period				T2 period			
	P1	P2	P3	P4	P1	P2	P3	P4
F50	10	50	48	143	6	68	27	115

Table 9 Customer zone demand for periods T1 and T2

CZ	T1 period				T2 period			
	P1	P2	P3	P4	P1	P2	P3	P4
C1	29	157	85	243	22	126	83	306
C2	23	149	95	264	21	116	91	303
C3	18	133	95	257	27	113	97	295
C4	26	102	89	313	22	103	80	278
C5	30	136	87	247	28	132	95	302
C6	24	123	90	312	28	155	80	306
C7	20	126	95	253	22	154	83	296
C8	23	128	85	235	29	146	97	253
C9	23	145	89	312	30	133	95	272
C10	23	139	91	303	23	128	88	313
C11	20	135	90	262	20	146	100	240
C12	22	135	99	317	20	153	98	283
C13	25	122	81	322	26	131	99	330
C14	27	120	99	327	24	148	100	277
C15	20	110	97	292	20	154	95	247
C16	25	143	93	287	20	103	99	311
C17	24	143	82	255	21	159	100	240
C18	21	134	95	238	23	139	98	263
C19	19	141	89	249	24	137	90	249
C20	19	101	85	284	23	155	99	285

Table 10 Quantity of product shipped from FCC to the hub in periods T1 and T2

FCC	T1 period															
	H1				H3				H4				H5			
	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4
F2		101	67	161	17		1	111								
F3					24	191	117	129	28	28	16	394				
F7		283		665	73		189									
F11	62	19	188	714		229										
F17	9	75	45	138												
F19	17	68	28	144												
F24									12	46	43	143				
F25	11		131		43	205		513								
F30	72	250	173	543												
F33					50			546		234	143					
F36	44	266	156	534												
F37									35	116	72	244			3	37
F38		119	69		30			262								
F39													34	141	88	243
F41		112	81		21			256								
F42	23	111	79	247												
F43													27	125	93	290
F47					35	163	100	424								
Total	238	1404	1017	3146	293	788	407	2241	75	424	274	781	61	266	184	570
FCC	T2 period															
	H1				H3				H4				H5			
	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4
F2	21	102	69	274												
F3					35		124			147	19	379				
F7	38	352	194		35			783								
F11		198	302	1066	104	265										
F17																
F19	19	52	39	149												
F24									5	58	35	139				
F25	52	212	47	266			98	219								
F30	63	186	163	518												
F33					1	157		446	43	76	148	89				
F36	43	233	141	504												
F37									26	119	53	265	4		15	
F38																
F39													11	135	81	263
F41																
F42	26	121	79	262												
F43													34	186	81	390
F47					45	243	166	504								
Total	262	1456	1034	3039	220	665	388	1952	74	400	255	872	49	321	177	653

Table 11 Quantity of product shipped from hub to CZ in periods T1 and T2

CZ	T1 period															
	H1				H3				H4				H5			
	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4
C1									29	157	85	243				
C2	6	118	95	264									17	31		
C3													18	133	95	257
C4													26	102	89	313
C5	30	136	87	247												
C6	24	123	90	312												
C7	20	126	95	253												
C8									23	128	85	235				
C9	23	145	89	312												
C10									23	139	91	303				
C11	20	135	90	262												
C12	22	135	99	317												
C13	25	122	81	322												
C14	27	120	99	327												
C15	20	110	97	292												
C16					25	143	93	287								
C17					24	143	82	255								
C18	21	134	95	238												
C19					19	141	89	249								
C20					19	101	85	284								
Total	238	1404	1017	3146	87	528	349	1075	75	424	261	781	61	266	184	570

CZ	T2 period															
	H1				H3				H4				H5			
	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4	P1	P2	P3	P4
C1									22	126	70	306				
C2	21	11	91	223										105		80
C3													27	113	97	295
C4													22	103	80	278
C5	28	132	95	302												
C6	28	155	80	306												
C7	22	154	83	296												
C8									29	146	97	253				
C9	30	133	95	272												
C10									23	128	88	313				
C11	20	146	100	240												
C12	20	153	98	283												
C13	26	131	99	330												
C14	24	148	100	277												
C15	20	154	95	247												
C16					20	103	99	311								
C17					21	159	100	240								
C18	23	139	98	263												
C19					24	137	90	249								
C20					23	155	99	285								
Total	262	1456	1034	3039	88	554	388	1085	74	400	255	872	49	321	177	653

Table 12 Status of inventory based on supply/demand of planning horizon T1–T10

		T1 period				T2 period			
Excess inventory at the end of a period to be used in the next period(s)	CZ	P1	P2	P3	P4	P1	P2	P3	P4
	C1			13					
	C2								
	–								
	C20								
To be expired inventory shipped in a period	C1								
	C2								
	–								
	C20	206	260	58	1166	132	111		867

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Affiliations

Rakesh Patidar[1] · **Sunil Agrawal**[1]

Rakesh Patidar
er.rakeshpatidar.sati@gmail.com

Sunil Agrawal
sa@iiitdmj.ac.in

[1] Department of Mechanical Engineering, PDPM Indian Institute of Information Technology, Design and Manufacturing, Jabalpur, India