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Design of multi-objective sustainable food distribution network in the Indian context with multiple delivery channels

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ABSTRACT

The paper addresses the design of a sustainable multiple-channel fresh food distribution network, which serves three purposes. Firstly, it addresses the changing preferences of consumers for online retailing. Secondly, the model investigates the distribution network of Buy Online Pickup in Store (BOPS) in the context of food supply chain. Thirdly, the model formulates new farming laws passed by the Indian government which allows the farmers to sell their produce as per their choice and removes the constraint of selling in the government regulated Mandis. To address the problem, a multiple-channel multi-objective fresh food distribution network model is developed. The model takes sustainability into consideration by formulating economic (total cost minimization), environmental (emission minimization) and social (delivery time minimization) objectives. A combination of an epsilon constraint and linear programming (LP) metrics method is used to solve the model. The applicability of the model is verified through a case study of a fresh tomato supply chain in India. Moreover, a sensitivity analysis is carried out to evaluate the different distribution strategies. Results show that demand ratio plays an important role in the identification of the optimal design with respect to the three objectives considered.

1. Introduction

Many economic activities such as manufacturing, tourism, sports, supply chain and logistics, have been impacted by the recent outbreak of the COVID-19 pandemic (Ivanov, 2020). The significant disruption in the food supply chain (FAO, 2020) paired with the significant effects of the purchasing behaviour of consumers moving to online ordering has impacted the choice of distribution channels. E-grocery orders have increased by 300% in the USA since the start of pandemic (FMI, 2020) and according to Mercatus and Incisiv (2020), e-grocery will contribute to 21.5% ($250 billion) of the total grocery market in the USA by 2025, 60% higher than previous estimates, attributed mainly to the COVID-19 pandemic. In India, the e-grocery sector is growing at a compound annual growth rate of 45–60% and is expected to reach $15–23 billion by 2025 (Research and Markets, 2020). However, last mile fulfilment with online ordering is a major concern for consumers in developing countries as they want good quality product at a cheaper price, but not all areas are sufficiently serviced. Consequently, another strategy is proposed: “buy online and pick up in store (BOPS)”. BOPS has increased in popularity to avoid the disadvantages associated with last mile fulfilment like, unattended delivery, difficulty in locating customer, and product returns. BOPS is highly effective in increasing sales and consumer satisfaction (Yadav & Singh, 2020), consequently, 42% of large retailers offer BOPS’s as an option to their consumers (eMarketer, 2016). Although BOPS costs less than last mile fulfilment with online ordering, it requires the customer to physically go and pick up the goods in store, therefore many companies aim to attract consumers by providing discounts to BOPS consumers (Yadav & Singh, 2020). The consumer’s experience could be enhanced even further by providing better online and offline flexibility, consequently, the retail giant needs to decide their optimal distribution strategy to provide seamless multiple-channel experience options to their consumers.

Recently, the Government of India passed a law called “The Farmers’ Produce Trade and Commerce (Promotion and Facilitation) Act, 2020” to allow the farmers to sell their own produce directly to consumers. The law promotes market competition by bringing in private players as well as reducing the number of intermediaries in the agro-food supply chain (AFSC) which take most of the profit. Previously, farmers were forced to

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sell their produce in the Mandis. In India, Mandis signify agricultural markets where produce is sold through auction. The process of selling in Mandis occurs through commission agents who mediate between the traders and farmers. Under the agricultural produce market committee (APMC) Act, the Mandis are regulated and controlled by the government. However, the operations of the APMC have been criticised for corruption and other malpractices (Gardas, Raut, Cheikhrouhou, & Narkhede, 2019) as officials often formed alliances to buy farmers' produce at cheaper rates. Consequently, the new law, in which direct selling by the farmer is a viable option, is being promoted by the government. The law was passed amid the COVID-19 situation to increase the income of farmers by providing them a competitive market environment. In addition, the law passed by the Indian government promotes the governmental agenda of doubling the farmers' income in the country by 2022. The government aims to provide farmers the access to new distribution channels in the AFSC to ensure rapid commercialisation of the produce. Thus, in this paper, a sustainable fresh food distribution network is designed, supporting farmers to sell their products directly to consumers. Through the proposed distribution network, consumers will have the flexibility to choose their preferred distribution channel. In particular, the BOPS distribution channel is investigated and evaluated.

The rest of the paper is organised as follows. The next section deals with relevant literature for the design of various distribution strategies and fresh food distribution network while problem description and model formulation of the proposed work is given in Section 3. The solution approach is discussed in Section 4. The numerical illustration is provided in Section 5 along with the results and their interpretation. Finally, concluding remarks and future scope of the work are presented in Section 6.

2. Literature review

2.1. Distribution strategies

In recent years, various distribution strategies have evolved to meet changing consumer preferences, from traditional distribution channels such as instore purchasing, to online retailing, which is growing at a very fast rate. Between these two extremes, many other distribution channels have evolved which are either different variant of these channels or integration of the same (Yadav, Tripathi, & Singh, 2017). For example, cross-channel distribution refers to performing a few of the activities in one channel while completing the other activities in another channel for the same transaction. Multiple-channel refers to providing more than one option of product delivery. Furthermore, today's consumers prefer the most convenient channel, thus, modern retail giants offer multiple channels to consumers and are slowly moving toward omnichannel (Yadav, Tripathi, & Singh, 2019). Omnichannel aims to make consumers shopping experience as seamless as possible (Rigby, 2011). Zhang, Lee, Wu, and Choy (2016) design a multiple channel distribution network with three objectives i.e., minimization of cost, minimization of carbon content and maximization of customer coverage using an Artificial Bee Colony algorithm to solve the proposed model. Bortolini, Galizia, Mora, Botti, and Rosano (2018) formulate a linear programming model to evaluate best distribution network configuration between direct, two stage and three stage shipping strategies. The objective is to minimize the total operating cost, delivery time and carbon footprint. The model is applied to a group of Italian producers who were distributing fresh fruits and vegetables to the European market using multi-mode transportation (i.e. truck, air, and train). Yadav et al. (2017) design a multiple channel distribution network using a mixed integer linear programming (MILP) model with the objectives of minimizing the costs and the environmental emissions, to provide the flexibility for consumers to choose their preferred distribution channel. They extend their model to incorporate service level (Yadav, Singh, & Jain, 2018) and uncertainty (Yadav et al., 2019). BOPS is a distribution strategy which is gaining a lot of attention from consumers in recent times (Yadav & Singh, 2020). Under the BOPS strategy, the consumer orders the product online and pick up their order from the store of their choice. Jin, Li, and Cheng (2018) studies the BOPS strategies and evaluates which type of product and cancellation policy should be adopted for BOPS. The authors also find the optimal ratio of unit inventory cost to the customer arrival rate to support selection of the service area for BOPS. Another popular distribution strategy is the last mile fulfilment; however, it is more costly than BOPS and faces various challenges such as unattended delivery, product returns and difficulty in locating customers. Deutsch and Golany (2018) propose a parcel locker network as a viable solution to last mile fulfilment problem and advocate providing discounts to consumers who travel to pick their orders from lockers. Prajapati, Harish, Daultani, Singh, and Pratap (2020) propose clustering-based routing heuristics for last mile fulfilment of fresh food regarding demand allocation, unmet demand and vehicle use to minimize the travel distance. In addition, Guerrero-Lorente, Gabor, and Ponce-Cueto (2020) formulate a mixed integer program (MIP) to design a parcel carrier network that manages online orders for the retailer to provide an omnichannel experience to the consumer. Singh, Kumar, Panchal, and Tiwari (2020) study the disruption caused by COVID-19 on logistics and food supply chain through a simulation study of the Indian PDS (Public Distribution System). The author highlights the need to build more a resilient supply chain to withstand pandemics like COVID-19.

2.2. Distribution network for fresh food supply chain

The design of distribution networks for fresh food is complex due to variables and constraints such as the deterioration of produce over time and transportation related issues. Ogier, Cung, and Boissière (2013) formulate a mixed integer program (MIP) for the distribution of fresh produce and using the "Bender decomposition and Dynamic slope scaling procedure" to solve location-allocation and transhipment decisions. Govindan, Jafarian, Khodaverdi, and Devika (2014) develop a sustainable supply chain network design SCND for two-echelon perishable produce with multi-vehicle routing problem (VRP) with time windows considering the minimization of cost and environmental impact to determine optimal location-allocation decisions. "Multi-Objective Particle Swarm Optimisation (MOPSO)" and adapted "multi-objective variable neighbourhood search algorithm" are utilised to solve the model and are compared with "Multi-Objective Genetic Algorithm – II (MOGA-II), Non-dominated Rank Genetic Algorithm (NRGA) and Non-dominated Sorting Genetic Algorithm – II (NSGA-II)." Furthermore, Suraraksa and Shin (2019) integrated location allocation and VRP time windows problem for distribution of fresh fruits and vegetables in Bangkok. The authors solve the location allocation in first phase and the VRP time windows problem in second phase using ant colony and tabu search algorithm that minimize travel distance and time and maximize demand coverage. Soysal, Bloemhof-Ruwaard, Haijema, and van der Vorst (2018) formulate a multi-objective linear programming (MOLP) to address the minimization of total logistics costs and greenhouse gas (GHG) emissions for a beef supply chain. GHG emissions are based on transportation activity (affected by travelled distances, weight loads of vehicles, road structure, vehicle, and fuel types), product perishability and return hauls. The authors utilise the ε-constraint method for solving the proposed model. Validi, Bhattacharya, and Byrne (2014) develop a robust model for the milk distribution in Ireland that minimized CO_2 emission and total cost and use NSGA II, MOGA-II and Hybrid GA to solve the proposed model, in which NSGA II outperformed the other two methods. Bai and Liu (2016) develop a robust optimisation model to capture uncertain transportation costs and demand through employing possibility distribution and test it on a supply chain network of a food processing industry. Rocco and Morabito (2016) develop one linear model along with three robust optimisation models dealing with uncertain data for the fresh tomato supply chain. The objective is to minimize the total cost of inventory, transportation, stock-out and

Table 1
Summary of fresh food supply chain.

Authors	Country	Focused produce	Sustainability aspect			Number of objectives		Network structure			Methodology adopted	Decisions	Objective function
			Ec	En	So	Single	Multiple	Traditional in-store	Online retailing or direct shipment	BOPS			
Ogier et al. (2013)	France	Fresh fruits and vegetables	√			√		√			MIP formulation, Dynamic Slope Scaling Procedure and Bender decomposition	Number of hubs and transportation services to be opened and flow of quantity between facilities	Minimization of total transportation and shortage cost
Soysal et al. (2018)	Brazil and European Union	Beef	√	√			√	√			MOLP formulation, ε -constraint and Pareto frontier	Inventory, allocation, number of trucks, number and quantity of livestock	Minimization of total logistic cost and GHG emission
Validi et al. (2014)	Ireland	Milk	√	√			√	√			Genetic algorithm and Pareto frontier	Transportation routes	Minimization of total cost and CO_2 emission
Govindan et al. (2014)	–	–	√	√			√	√	√		Hybrid approach with time windows, MOPSO, MOVNS, MOGA, NRGA, NSGA-II	Location, allocation and vehicle routes	Minimization of total logistics cost and CO_2 emission
Bai and Liu (2016)	–	Roast chicken	√			√		√			Parameter-based domain decomposition method, MIP formulation, parametric optimisation	Location and allocation at facilities, preferred risk and service level	Minimizing VaR of total cost at given confidence level
Bortolini, Faccio, Gamberi, and Pilati (2016)	Italy, Austria, France, Spain, Germany, Czech Republic, Netherlands, and Portugal	Fresh fruits and vegetables	√	√	√		√	√	√		MOLP formulation and weighing auxiliary function	Shipment strategy, transportation modes and quantity of flows	Minimization of operating cost, carbon footprints and delivery time
Rocco and Morabito (2016)	Brazil	Tomato	√			√		√			LP formulation and robust optimisation	Inventory, location and allocation decisions	Minimization of logistics and total production cost
Ghezavati et al. (2017)	Iran	Tomato	√			√		√			MIP formulation and bender decomposition	Allocation and inventory decisions	Maximization of profit
Mohammed and Wang (2017a)	UK	Meat	√		√		√	√			Possibilistic programming, LP-metrics, ε -constraint, and the weighted Tchebycheff method	Number and allocation of abattoirs and farms, flow quantity of meat and livestock	Minimization of total transportation cost, delivery time and transportation vehicles
Mohammed and Wang (2017b)	UK	Meat	√	√	√		√	√			Fuzzy programming, the ε -constraint LP-metrics and goal programming method	Product flow quantity, number and location of facilities	Minimization of total transportation cost, delivery time and carbon footprints Maximization of average delivery rate
Musavi and Bozorgi-Amiri (2017)	–	–	√	√	√		√	√			MO-MILP formulation, Meta heuristic, NSGA-II, Pareto solutions	Location, allocation and scheduling decisions	Minimization of total transportation cost and CO_2 emission Maximization of produce quality
Allaoui et al. (2018)	–	–	√	√	√		√	√			MILP formulation, two stage hybrid approach, AHP, ordered weighted averaging aggregation method, Pareto frontier	Number and location of effective distributors, transformers and suppliers	Minimization of total transportation cost, CO_2 emission, job creation/ destruction and water consumption Maximization of sites efficiency

(*continued on next page*)

Table 1 (*continued*)

Authors	Country	Focused produce	Sustainability aspect			Number of objectives		Network structure			Methodology adopted	Decisions	Objective function
			Ec	En	So	Single	Multiple	Traditional in-store	Online retailing or direct shipment	BOPS			
Bortolini et al. (2018)	Italy	Fresh fruits and vegetables						√	√		MILP formulation and Pareto frontier	Location of storage/ handling node, allocations of flows and selection of best packaging container, transportation modes	Minimization of cost and emission
Chao, Zhihui, and Baozhen (2019)	China	Fresh Fruit, vegetable, meat and sea-food	√			√		√			MIP formulation, hybrid heuristic, distance based clustering, relocate exchange and improved ACO	Location, allocation, inventory, time windows and vehicle routing	Minimization of total cost of distribution process
Rohmer et al. (2019)	Netherlands	Beef and dairy chain	√	√	√		√	√			Compromise programming and e-constraint method	Consumption, transportation, processing and sourcing decisions	Minimization of cost and environmental impact
Suraraksa and Shin (2019)	Thailand	Fresh fruit and vegetable	√	√		√			√		Two phase LAP and VRPTW formulation, Ant colony and Tabu search	Location, allocation, number of vehicle and their routes with time windows	Minimization of travel distance, travel time and maximization coverage and fairness among drivers
Patidar and Agrawal (2020a)	India	Fresh Vegetable (3 type of shelf life)	√			√		√			MILP formulation and LINGO software	Hub location, allocation, quantity of expired product and inventory decisions	Minimization of total cost
Patidar and Agrawal (2020b)	India	Fresh Vegetable (4 type of shelf life)	√			√		√			MINLP formulation and LINGO software	Location, allocation, quantity of expired product and inventory decisions	Minimization of total cost
Prajapati et al. (2020)	India	—	√			√			√		Clustering based routing heuristics and LINGO software	Allocation, vehicle number and type, weight of delivered and non-delivered product	Minimization of total travel distance
Yakavenka et al. (2020)	Greece and North Eastern Europe	Fruits	√	√	√		√	√			MILP formulation, goal programming	Location and allocation decisions, transportation mode and selection of routes	Minimization of total transportation cost, carbon footprints and delivery time
This paper	India	Tomato	√	√	√		√	√	√	√	MILP formulation, integrated epsilon -constraint and LP metric method	Location and allocation decisions, shipment strategy,	Minimization of total transportation cost, carbon emissions and delivery time

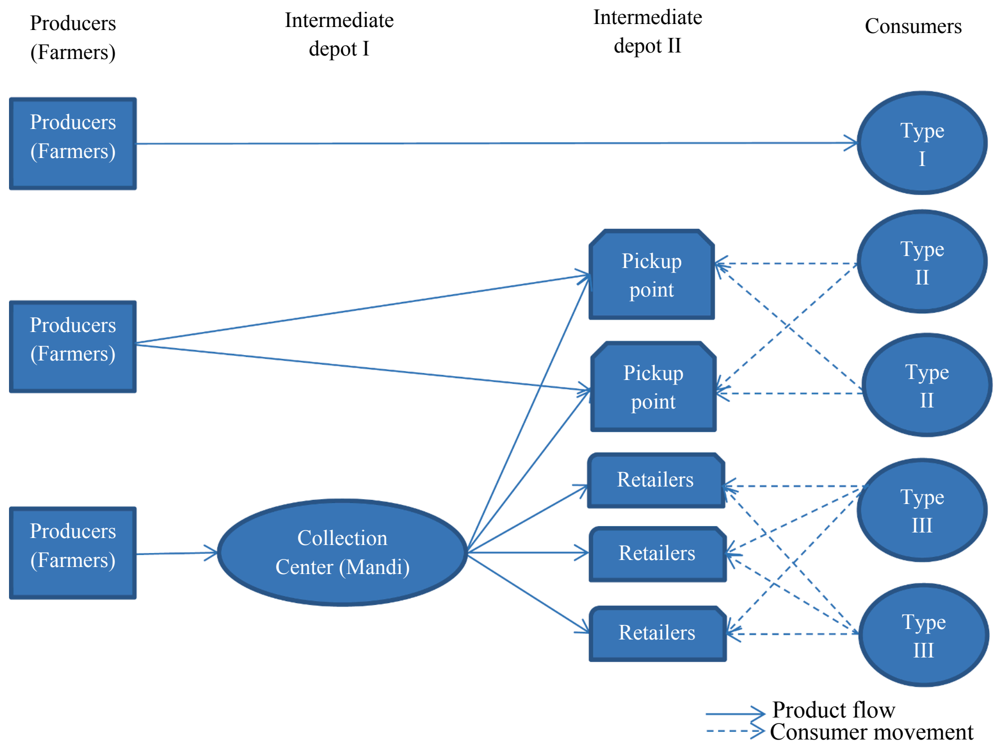

Fig. 1. Schematic representation of the proposed model.

procurement. Ghezavati, Hooshyar, and Tavakkoli-Moghaddam (2017) formulate a mathematical model for the distribution of fresh tomato supply chain utilising Bender's decomposition method to maximize the retailer's profit. Mogale, Cheikhrouhou, and Tiwari (2020) formulate a bi-objective mixed integer non-linear multi-period, multi-modal, multi-echelon, multi sourcing and distribution programming model for minimizing both total cost and CO_2 emissions. Patidar and Agrawal (2020a) consider three types of shelf life (1, 2 and 3 days) for fresh vegetables and formulated a MILP model to minimize total cost in the Indian context. The authors find that the proposed model performs better in handling food losses than the traditional network. They extend the model to MINLP in (Patidar & Agrawal, 2020b) considering more type of shelf life and minimizing the distance travelled by farmers to reach the hub location to sell their produce.

Significant research exists in the environmental and economic dimension of sustainability; however, the social aspects are rarely considered independently (Eskandarpour, Dejax, Miemczyk, & Péton, 2015). Mohammed and Wang (2017a) formulate a three-echelon multi-objective distribution network for a meat supply chain in the UK with the objective to minimize distribution time, transportation cost, and number of vehicles to reduce CO_2. Three approaches are utilised to solve the proposed model, namely the ε-constraint method, LP-metrics method, and weighted Tchebycheff method, using TOPSIS to rank the Pareto optimal solution for trade-off purposes. Mohammed and Wang (2017b) extend their initial model to incorporate the maximization of the average delivery rate. Musavi and Bozorgi-Amiri (2017) propose tri-objective design of distribution network which comprises the maximization of carbon emission, transportation cost and maximization of produce quality. Bortolini et al. (2018) formulate a multi-objective linear programming model to design multi-modal distribution network for Italian fresh food with the objective to minimize cost, carbon footprint and delivery time. Allaoui, Guo, Choudhary, and Bloemhof (2018) use a two-stage methodology to elaborate a trade-off between numbers of jobs created, water footprint, carbon footprint and total cost associated with the design of the AFSC. Rohmer, Gerdessen, and Claassen (2019) analyse the trade-off between cost and emissions by investigating the impact of switching to a plant-based diet from meat-based diet. The social aspects in their work are modelled as constraints. Yakavenka, Mallidis, Vlachos, Iakovou, and Eleni (2020) design a tri-objective fruit AFSC to minimize carbon emissions, cost, and delivery time of a case study in Greece and North-eastern Europe using goal programming as the solution methodology. Table 1 shows a comparison of the relevant literature related to the design of fresh AFSC.

2.3. Research gaps

Based on the literature review, a few significant research gaps are identified:

- Since COVID-19 pandemic has started to change consumer preferences (Ivanov, 2020), sales channel choice is one such prominent aspect. In this regard, BOPS is a shipment strategy that has not been investigated in the current literature for fresh AFSC.
- Direct shipment (through online trading) of agricultural produce is rarely addressed in the fresh AFSC literature. There is no literature in the Indian context dealing with the design of distribution networks since direct shipment from farmers is a process that was not allowed in the past. As the Government of India currently opens the way to the farmers to sell their produce in an open market, direct shipment should be assessed and considered in the design strategies of fresh food supply chains.
- Only two sustainability dimensions, i.e. environmental and economic, are prevalent in the literature, while the societal pillar is not much discussed for fresh AFSC.

3. Problem description and model formulation

We consider a multiple channel distribution network as presented in Fig. 1, that considers three shipment strategies i.e., in store purchase (traditional distribution network), BOPS and direct shipment (online ordering). The proposed network comprises of producers (group of farmers), two intermediate depot and customer zones. The first

Table 2
Decision variables and their descriptions.

Decision variables	Description
x_{fc}^m	Quantity of produce (in Kg.) transported from node f (farmer) to node c (collection center) through transportation mode $m = 1,2,\cdots M$
x_{cr}^m	Quantity of produce (in Kg.) transported from node c (collection center) to node r (retail outlet) through transportation mode $m = 1,2,\cdots M$
x_{cp}^m	Quantity of produce (in Kg.) transported from node c (collection center) to node p (pickup point) through transportation mode $m = 1,2,\cdots M$
x_{fp}^m	Quantity of produce (in Kg.) transported from node f (farmer) to node p (pickup point) through transportation mode $m = 1,2,\cdots M$
x_{fk}^m	Quantity of produce (in Kg.) transported from node f (farmer) to node k (customer) through transportation mode $m = 1,2,\cdots M$
y_{fk}^m	Binary variables denoting $\left\{\begin{matrix} 1 \text{ if the transportation mode } m \text{ is selected from node } f \text{ to node } k \\ 0 \text{Otherwise} \end{matrix}\right\}$
y_{fp}^m	Binary variables denoting $\left\{\begin{matrix} 1 \text{ if the transportation mode } m \text{ is selected from node } f \text{ to node } p \\ 0 \text{Otherwise} \end{matrix}\right\}$
y_{fc}^m	Binary variables denoting $\left\{\begin{matrix} 1 \text{ if the transportation mode } m \text{ is selected from node } f \text{ to node } c \\ 0 \text{Otherwise} \end{matrix}\right\}$
y_{cp}^m	Binary variables denoting $\left\{\begin{matrix} 1 \text{ if the transportation mode } m \text{ is selected from node } c \text{ to node } p \\ 0 \text{Otherwise} \end{matrix}\right\}$
y_{cr}^m	Binary variables denoting $\left\{\begin{matrix} 1 \text{ if the transportation mode } m \text{ is selected from node } c \text{ to node } r \\ 0 \text{Otherwise} \end{matrix}\right\}$
y_c	Binary variables $\left\{\begin{matrix} 1 \text{ if the node } c \text{ is open} \\ 0 \text{Otherwise} \end{matrix}\right\}$
y_r	Binary variables $\left\{\begin{matrix} 1 \text{ if the node } r \text{ is open} \\ 0 \text{Otherwise} \end{matrix}\right\}$
y_p	Binary variables $\left\{\begin{matrix} 1 \text{ if the node } p \text{ is open} \\ 0 \text{Otherwise} \end{matrix}\right\}$

intermediate depot is a collection center, which is often known as 'Mandi' in the Indian context and is positioned near producers. The second intermediate depot comprise of two types of facilities i.e., retailers and pickup points. The customer zones are further divided into three types in which the first type of customer zones receive produce directly from producers by ordering online. The second type of customer zones order online and receive the produce by picking it up from nearest pick up point. The third type of customer zones receives the produce from retailers through physical ordering and visits. The proposed distribution configuration is in line with the recent law passed by the Indian Government which allows farmers to sell their produce directly on the open market. Previously, such activities were not allowed, however, now industries are facilitating online purchasing behaviour, which is expected to continue. The model representing the distribution design problem of fresh food considers three sustainability objectives i.e., the minimization of total cost as the economic criterion, the minimization of CO_2 emissions as the environmental criterion and the total system-wide time minimization as the societal criterion. The final goal is to identify the optimal distribution strategy, the locations and allocation of the facilities.

The assumptions used in the development of the model are:

1. Demand is deterministic and all the details about facilities are known in advance.
2. The operational cost includes inventory and all other related costs at concerned facilities.
3. The model is formulated for single produce only.
4. Food loss and quality decay are not considered.
5. Producers have sufficient capacity to fulfil all customers' demands.

Table 2 and Table 3 introduce the decision variables and the notations used in the proposed model, respectively.

$$\min Z_1 = \sum_{c\in C} c_f y_c + \sum_{r\in R} r_f y_r + \sum_{p\in P} p_f y_p + \sum_{f\in F}\sum_{c\in C}\sum_{m=1}^{M} c_{fc}^m x_{fc}^m + \sum_{c\in C}\sum_{r\in R}\sum\nolimits_{m=1}^{M} c_{cr}^m x_{cr}^m + \sum_{c\in C}\sum_{p\in P}\sum_{m=1}^{M} c_{cp}^m x_{cp}^m + \sum_{f\in F}\sum_{p\in P}\sum\nolimits_{m=1}^{M} c_{fp}^m x_{fp}^m + \sum_{f\in F}\sum_{k\in K}\sum\nolimits_{m=1}^{M} c_{fk}^m x_{fk}^m + \sum_{k\in K}\sum_{p\in P} c_{kp}\left(x_{fp}^m + x_{cp}^m\right) + \rho^* \sum_{c\in C} x_{fc}^m + \sigma^* \sum_{p\in P}\left(x_{fp}^m + x_{cp}^m\right) + \tau^* \sum_{r\in R} x_{cr}^m \quad (1)$$

Equation 1 denotes objective 1, which consists of the minimization of the total cost including fixed costs of opening a facility, transportation cost between the facilities, discount offered to customers and operational costs at the facilities.

$$\min Z_2 = \sum_{c\in C} c_e y_c + \sum_{r\in R} r_e y_r + \sum_{p\in P} p_e y_p + \sum_{f\in F}\sum_{c\in C}\sum_{m=1}^{M} e_{fc}^m x_{fc}^m + \sum_{c\in C}\sum_{r\in R}\sum\nolimits_{m=1}^{M} e_{cr}^m x_{cr}^m + \sum_{c\in C}\sum_{p\in P}\sum_{m=1}^{M} e_{cp}^m x_{cp}^m + \sum_{f\in F}\sum_{p\in P}\sum\nolimits_{m=1}^{M} e_{fp}^m x_{fp}^m + \sum_{f\in F}\sum_{k\in K}\sum\nolimits_{m=1}^{M} e_{fk}^m x_{fk}^m + \theta^* \sum_{c\in C} x_{fc}^m + \vartheta^* \sum_{p\in P}\left(x_{fp}^m + x_{cp}^m\right) + \mu^* \sum_{r\in R} x_{cr}^m \quad (2$$

Equation 2 denotes objective 2, which is the minimization of total carbon emission from three sources i.e., fixed facilities, transportation between facilities and operational activities at various facilities.

$$\min Z_3 = \sum_{f\in F}\sum_{c\in C}\sum_{m=1}^{M} t_{fc}^m y_{fc}^m + \sum_{c\in C}\sum_{r\in R}\sum_{m=1}^{M} t_{cr}^m y_{cr}^m + \sum_{c\in C}\sum_{p\in P}\sum_{m=1}^{M} t_{cp}^m y_{cp}^m + \sum_{f\in F}\sum_{p\in P}\sum_{m=1}^{M} t_{fp}^m y_{fp}^m + \sum_{f\in F}\sum_{k\in K} t_{fk} y_{fk} \quad (3)$$

Equation 3 denotes objective 3, which is minimization of total system-wide delivery time from source of production to source of consumption.

Subjected to:

$$\sum_{f\in F}\sum_{m=1}^{M} x_{fc}^m = \sum_{p\in P}\sum_{m=1}^{M} x_{cp}^m + \sum_{r\in R}\sum_{m=1}^{M} x_{cr}^m \quad \forall c \in \quad (4)$$

$$\sum_{f\in F}\sum_{m=1}^{M} x_{fk}^m + \sum_{p\in P}\sum_{m=1}^{M}\left(x_{fp}^m + x_{cp}^m\right) + \sum_{r\in R}\sum_{m=1}^{M} x_{cr}^m = K_d \quad \forall f \in F, \forall p \in P, \forall r \in R \quad (5)$$

$$\sum_{f\in F}\sum_{m=1}^{M} x_{fk}^m = \alpha^* K_d \quad (6)$$

$$\sum_{p\in P}\sum_{m=1}^{M}\left(x_{fp}^m + x_{cp}^m\right) = \beta^* K_d \quad 7)$$

$$\sum_{r\in R}\sum_{m=1}^{M} x_{cr}^m = \gamma^* K_d \quad 8)$$

$$\alpha + \beta + \gamma = 1 \quad (9)$$

Capacity constraints:

Table 3
Parameters and their descriptions.

Parameters	Description
c_{fc}^m	Cost for transporting per Kg. produce from node f to node c through transportation mode$m$
c_{cr}^m	Cost for transporting per Kg. produce from node c to node r through transportation mode$m$
c_{cp}^m	Cost for transporting per Kg. produce from node c to node p through transportation mode$m$
c_{fp}^m	Cost for transporting per Kg. produce from node f to node p through transportation mode$m$
c_{fk}^m	Cost for transporting per Kg. produce from node f to node k through transportation mode$m$
c_{kp}	Discount offered to customer for picking per Kg. produce by travelling from node k to node$p$
c_f	Fixed cost of collection centers
r_f	Fixed cost of retail outlets
p_f	Fixed cost of pick-up points
ρ	Operational cost per Kg. at collection centers
σ	Operational cost per Kg. at pickup points
τ	Operational cost per Kg. at retail outlets
cap_f	Capacity of producers
cap_c	Capacity of collection center
cap_r	Capacity of retail outlets
cap_p	Capacity of pickup points
e_{fc}^m	The quantity of emissions generated by transporting one Kg of produce from node f to node c through transportation mode$m$
e_{cr}^m	The quantity of emissions generated by transporting one Kg of produce from node c to node r through transportation mode$m$
e_{cp}^m	The quantity of emissions generated by transporting one Kg of produce from node c to node p through transportation mode$m$
e_{fp}^m	The quantity of emissions generated by transporting one Kg of produce from node f to node p through transportation mode$m$
e_{fk}^m	The quantity of emissions generated by transporting one Kg of produce from node f to node k through transportation mode$m$
c_e	Emissions due to establishment of collection center
p_e	Emissions due to establishment of pickup point
r_e	Emissions due to establishment of retail outlets
θ	Emissions generated per Kg. due to various activities at collection centers
ϑ	Emissions generated per Kg. due to various activities at pickup point
μ	Emissions generated per Kg. due to various activities at retail outlets
k_d	Demand of customer$d$
t_{fc}^m	Transportation time from node f to node c through transportation mode$m$
t_{cr}^m	Transportation time from node c to node r through transportation mode$m$
t_{cp}^m	Transportation time from node c to node p through transportation mode$m$
t_{fp}^m	Transportation time from node f to node p through transportation mode$m$
t_{fk}^m	Transportation time from node f to node k through transportation mode$m$
ϵ	Maximum allowable transportation time depending on produce's shelf-life
α	Percentage of demand to be meet by online mode
β	Percentage of demand to be meet by BOPS mode
γ	Percentage of demand to be meet by retail outlets mode

$$\sum_{c\in C}\sum_{m=1}^{M}x_{fc}^m+\sum_{p\in P}\sum_{m=1}^{M}x_{fp}^m+\sum_{k\in K}\sum_{m=1}^{M}x_{fk}^m\leq\sum_{f\in F}cap_f*y_f\quad\forall f\in F,\forall p\in P,\forall c\in C,\forall r\in R,\forall k\in K \tag{10}$$

$$\sum_{p\in P}\sum_{m=1}^{M}x_{cp}^m+\sum_{r\in R}\sum_{m=1}^{M}x_{cr}^m\leq\sum_{c\in C}cap_c*y_c\quad\forall c\in C,\forall p\in P \tag{11}$$

$$\sum_{k\in K}\sum_{m=1}^{M}\left(x_{fp}^m+x_{cp}^m\right)\leq\sum_{p\in P}cap_p*y_p\quad\forall p\in P,\forall k\in K \tag{12}$$

$$\sum_{k\in K}\sum_{m=1}^{M}x_{cr}^m\leq\sum_{r\in R}cap_r*y_r\quad\forall r\in R,\forall k\in K \tag{13}$$

Transportation modes constraints:

$$\sum_{f\in F}\sum_{k\in K}\sum_{m=1}^{M}y_{fk}^m=1 \tag{14}$$

$$\sum_{f\in F}\sum_{p\in P}\sum_{m=1}^{M}y_{fp}^m=1 \tag{15}$$

$$\sum_{f\in F}\sum_{c\in c}\sum_{m=1}^{M}y_{fc}^m=1 \tag{16}$$

$$\sum_{c\in C}\sum_{p\in P}\sum_{m=1}^{M}y_{cp}^m=1 \tag{17}$$

$$\sum_{c\in C}\sum_{r\in R}\sum_{m=1}^{M}y_{cr}^m=1 \tag{18}$$

Binary constraints

$$y_{fk}^m,y_{fp}^m,y_{fc}^m,y_{cp}^m,y_{cr}^m,y_c,y_r,y_p\in\{0,1\}\quad\forall f\in F,\forall p\in P,\forall c\in C,\forall r\in R \tag{19}$$

Non-negativity constraints

$$x_{fk}^m,x_{fp}^m,x_{fc}^m,x_{cp}^m,x_{cr}^m,\geq 0 \tag{20}$$

Equations 4 to 9 are the flow constraints which maintain the smooth flow of products between various echelons of the proposed network. Equation 4 denotes that the produce quantity transported from farmers to the collection centers is equal to the sum of produce quantity to be transported from the collection centers to the pickup points and retail outlets, respectively. Equation 5 ensures that the total demand is satisfied by produce received from farmers, the pickup points and retail outlets. Equation 6, 7 and 8 denote the fraction of demand received from farmers (through direct shipment), from the pickup points and retail outlet channels, respectively. Equation 9 denotes that all demand fractions should be equal to one. Equations 10 to 13 are capacity constraints for producers, collection centers, pickup points, and retailers, respectively. Equations 14, 15 and 16 ensure single mode of transportation from farmers to demand zone, pickup points, and collection centers, respectively. Equation 17 and 18 ensure single mode of transportation from collection centers to pickup points and retail outlets, respectively. Equation 19 and 20 are binary and non-negativity constraints for decision variables, respectively.

4. Solution approach

The proposed model is a multi-objective mixed integer linear program (MILP) for which there is several possible solving methods. We develop two methods in this paper, the epsilon constraint method and the linear programming (LP) metrics method.

4.1. Epsilon constraint method

Epsilon constraint prioritises the primary objective while the other objectives are expressed as a constraint to the primary objective (Eskandarpour et al., 2015). In our case, we use the economic and environmental objectives as primary objectives, and the social objective is considered as the constraint. Consequently, the proposed model could be expressed as follows:

Table 4
Results of different scenarios for the case 1.

Scenario No.	w1	w2	Objective function 1 (in Rupees)	Objective function 2 (in CO2 Kg.)	Objective function 3 (in hours)	Open collection centers	Open pickup points	Open retail outlets
1	0	1	62,724	4978.78	44.64	1,3	1	1,9,10
2	0.1	0.9	62975.2	5037.656	45.1	1,3	1	1,9,10
3	0.2	0.8	62975.2	5037.656	45.1	1,3	1	1,9,10
4	0.3	0.7	62975.2	5037.656	45.1	1,3	1	1,9,10
5	0.4	0.6	62975.2	5037.656	45.1	1,3	1	1,9,10
6	0.6	0.4	62980.2	5038.656	61.9	1,3	1	1,2,10
7	0.7	0.3	62980.2	5038.656	61.9	1,3	1	1,2,10
8	0.8	0.2	62980.2	5038.656	54	1,3	1	1,2,10
9	0.9	0.1	62,236	5182.86	54.675	1,3	1	1,9,10
10	1	0	62,098	5191.44	57.845	1,3	4,6	1,9,10

Table 5
Effects of demand on various channels [case 2].

Scenario No.	Demand ratio (online-BOPS-retail) (in % of total demand)	w1	w2	Objective function 1 (in Rupees)	Objective function 2 (in CO2 Kg.)	Objective function 3 (in hours)	Open collection centers	Open pickup point	Open retail outlets
1	0-50-50	0.5	0.5	60,955	4756.24	47.675	1	1,2,3	1,5,10
2	20-40-40	0.5	0.5	58,753	4561.78	48.14	1	1,2,3	1,10
3	40-30-30	0.5	0.5	57,473	4421.64	48.675	1	2,3	5,10
4	60-20-20	0.5	0.5	55,376	4269.76	43.005	1	1	10
5	80-10-10	0.5	0.5	53,553	4090.82	44.68	3	3	10
6	100-0-0	0.5	0.5	51,540	3915	32.5	–	–	–
7	50-0-50	0.5	0.5	60,724	4817.58	37.99	1	–	1,5,10
8	40-20-40	0.5	0.5	58,604	4587.78	37.24	1	1	1,10
9	30-40-30	0.5	0.5	57,193	4401.64	48.695	1	1,3,6	5,10
10	20-60-20	0.5	0.5	55,517	4204.26	60.655	1	1,2,3,6	10
11	10-80-10	0.5	0.5	54,260	4008.72	65.87	3	1,2,3,4,5	10
12	0-100-0	0.5	0.5	52,340	3829.9	51.82	–	1,2,3,4,5,6	–
13	50-50-0	0.5	0.5	51,869	3888	48.12	–	1,2,3	–
14	40-40-20	0.5	0.5	55,777	4248.26	54.925	1	2,3,6	10
15	30-30-40	0.5	0.5	58,774	4575.28	42.86	1	1,2	1,10
16	20-20-60	0.5	0.5	62980.2	5038.656	54	1,3	1	1,2,10
17	10-10-80	0.5	0.5	68,264	5555.12	65.91	1,2,3	3	1,2,9,10
18	0-0-100	0.5	0.5	74110.5	6163.675	69.885	1,2,3	–	2,3,4,5,6,7,8,10

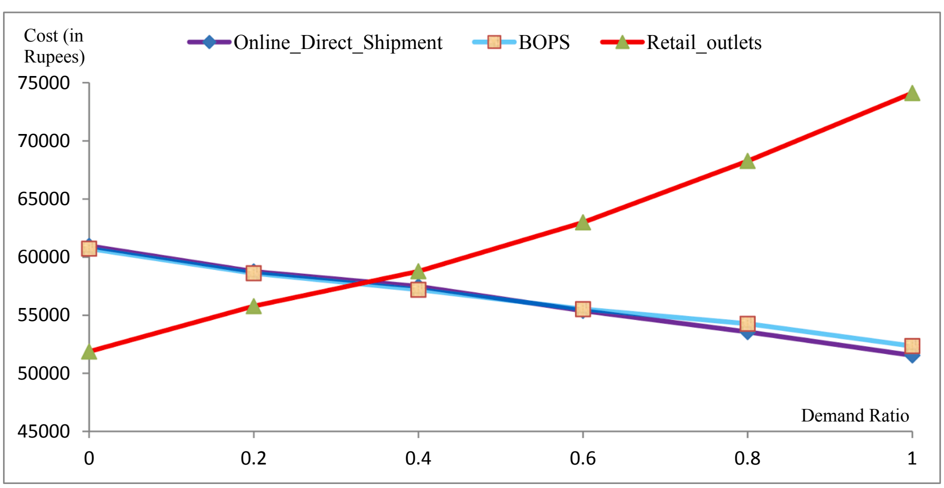

Fig. 2. Variation of total economic cost with respect to demand ratio in all three channels.

$\min Z_1$ *and* $\min Z_2$

Subjected to constraints (4) to (20), and

$$Z_3 \leq \epsilon \quad (21)$$

It is interesting to note that system wide minimization of delivery time consists of three shipment strategies for three types of consumers through four delivery routes. Hence, delivery time per route should be less than a prescribed maximum allowable time (i.e., ϵ in our case). Therefore, Equation 21 can be broken down into four series of equations (i.e., for four delivery routes) as follows:

$$t^m_{fk} y^m_{fk} \leq \epsilon \quad \forall f \in F, \forall k \in K \quad (22)$$

$$t^m_{fp} y^m_{fp} \leq \epsilon \quad \forall f \in F, \forall p \in P \quad 23)$$

$$t^m_{fc} y^m_{fc} + t^m_{cr} y^m_{cr} \leq \epsilon \quad \forall f \in F, \forall c \in C, \forall r \in R \quad (24)$$

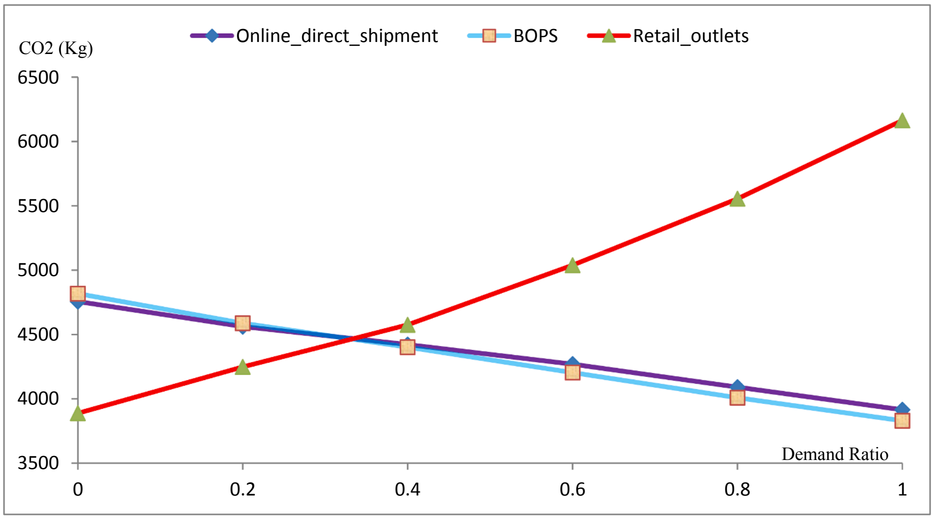

Fig. 3. Variation of carbon emission cost with respect to demand ratio in all three channels.

Table 6
Data from producer to customer zone and capacity of producer.

	D1	D2	D3	D4	Capacity (in Kg.)
Pakargaon	5.2/0.4/6.38	5.4/0.42/6.4	5.3/0.42/6.39	5.25/0.425/6.395	3000
Ludeg	5.1/0.39/6.32	5.1/0.4/6.32	5.3/0.426.39	5.2/0.42/6.38	2000
Saraitola	4.8/0.35/5.94	4.8/0.35/5.94	5/0.35/5.96	5.1/0.41/6.32	2500
Chiknipani	5.3/0.41/6.54	5.25/0.425/6.395	5.3/0.41/6.39	5.2/0.42/6.38	1800
Bagbahar	6/0.46/7.32	5.8/0.46/7.1	6/0.48/7.32	5.9/0.48/7.2	1500

Table 7
Data from producer to pickup point.

	P1	P2	P3	P4	P5	P6
Pakargaon	4.16/0.35/5.74	4.12/0.35/5.7	4.23/0.36/5.8	4.2/0.35/5.78	4.12/0.34/5.7	4.15/0.34/5.73
Ludeg	4.080.34/5.67	4/0.32/5.62	4/0.32/5.62	4.12/0.35/5.69	4.12/0.35/5.69	4.1/0.34/5.68
Saraitola	3.6/0.28/5.35	3.5/0.28/5.33	3.5/0.28/5.33	3.6/0.29/5.35	3.5/0.28/5.33	3.5/0.28/5.33
Chiknipani	4.24/0.34/5.89	4.22/0.34/5.87	4.26/0.35/5.91	4.24/0.35/5.89	4.24/0.35/5.89	4.22/0.35/5.87
Bagbahar	4.5/0.36/6.59	4.55/0.38/6.6	4.5/0.36/6.59	4.5/0.36/6.59	4.6/0.37/6.62	4.6/0.37/6.62

$$t^m_{fc}y^m_{fc} + t^m_{cp}y^m_{cp} \leq \epsilon \quad \forall f \in F, \forall c \in C, \forall p \in P \tag{25}$$

4.2. LP-metric method

The LP-metric method combines a multi-objective problem into a single dimensionless objective. For this, it requires the knowledge of optimal value for each objective. For our case, as the tri-objective problem has already been converted into bi-objective by the ϵ –constraint method, we need to combine the bi-objective into single dimensionless objective as follows:

$$Z_4 = w_1\frac{Z_1 - Z_1^*}{Z_1} + w_2\frac{Z_2 - Z_2^*}{Z_2} \tag{25}$$

where Z_1 and Z_2 are objective functions whileZ_1^* andZ_2^* are their respective optimal values. w_1 and w_2 are the weight preferences whose summation is equal to one. The decision makers decide the weights as per their requirements. Thus, the new model formulation is as follows:

$$Min\ Z_4 \tag{26}$$

Subject to constraints (4) to (20) and constraints (22) to (25).

Following this procedure, the obtained model can be coded in any suitable solver like CPLEX, MS-Excel and Gurobi to get the optimum value of each objective.

5. Numerical illustrations and results

This section presents the analysis of a real case of tomato supply chain in Chhattisgarh of central India using the proposed model. The

Table 8
Data from producers to collection centers.

	Pathalgaon	Pharsabahar	Kansabel	Duldula
Pakargaon	0.936/0.0745/0.105	7.02/0.5616/0.86	4.68/0.3744/0.55	13.104/1.0483/1.54
Ludeg	1.02/0.0918/0.26	3.06/0.2754/0.97	1.785/0.1607/0.49	4.08/0.3672/1.24
Saraitola	0.912/0.073/0.43	1.2768/0.1021/0.61	0.6384/0.0511/0.31	1.824/0.1459/1.06
Chiknipani	1.06/0.0954/0.43	1.696/0.1526/0.69	0.848/0.0763/0.39	2.332/0.2099/1.14
Bagbahar	1.2/0.108/0.525	1.2/0.108/0.52	0.6/0.216/0.31	2.4/0.2592/1.06

Table 9
Data from collection center to pickup point and capacity, fixed cost, and fixed emission of collection centers.

	P1	P2	P3	P4	P5	P6	Capacity (in Kg.)	FC/FE
Pathalgaon	4/0.36/6.026	3.9/0.312/5.9	4.2/0.378/6.2	4.12/0.3296/6.1	4.2/0.378/6.2	4.12/4.12/6.1	5000	400/48
Pharsabahar	4.68/0.3978/8.102	4.7/0.423/8.15	4.75/0.38/8.2	4.65/0.4185/8	4.56/0.3648/8.15	4.7/0.423/8.15	3000	275/27.5
Kansabel	4.32/0.3672/6.812	4.3/0.3655/6.75	4.3/0.387/6.75	4.4/0.352/6.9	4.35/0.3915/6.8	4.4/0.352/6.9	2500	250/24
Duldula	5.04/0.4284/8.776	5/0.425/8.7	5/0.425/8.7	5.1/0.459/8.8	5.2/0.416/8.85	4.95/0.4455/8.6	2500	250/24

Table 10
Data from pickup point to customer zone and capacity, fixed cost, and fixed emission of pickup point.

	D5	D6	D7	D8	D9	D10	Capacity (in Kg.)	FC/FE
P1	0.5	0.55	0.5	0.55	0.5	0.5	2000	80/8
P2	0.6	0.6	0.6	0.6	0.6	0.55	1600	70/7.5
P3	0.55	0.55	0.55	0.6	0.55	0.55	1400	65/6.5
P4	0.6	0.6	0.65	0.55	0.55	0.55	1800	75/8
P5	0.7	0.7	0.65	0.7	0.65	0.6	2000	80/8.4
P6	0.5	0.55	0.6	0.55	0.55	0.55	1600	70/7.5

Here value denotes the discount per Kg. (in Rupees).

Jashpur district (under Surguja division) is commonly known as the tomato capital of Chhattisgarh. The tomato production in this area is so high that one village, Ludeg, is called 'the tomato village'. The case of a Raipur-based food retailer which intends to sell the tomatoes through multiple channels is studied. Furthermore, to maintain confidentiality and avoid any competitive loss to the organisation, the retailer will be referred to as the 'case organisation' hereafter in this work. The case organisation has taken the decision to provide a multiple channel facility amid the government's decision to allow the farmers to sell their product in an open market. The case organisation wishes to establish itself as a major player in tomato market and has identified five tomato producing villages namely Pakargaon, Ludeg, Saraitola, Chiknipani and Bagbahar to source the tomatoes, in addition to four collection centers (known as Mandis) near these tomato producing villages: in Pathalgaon, Pharsabahar, Kansabel and Duldula. The market for tomato is in Raipur, which includes retail outlets and pick-up points. Thus, the full distribution network consists of 5 producers, 4 collection centers, 10 retail outlets, 6 pickup stations and 20 customer zones. Here, the transportation medium for tomatoes is only by road as rail and air transportation is not available. Two types of trucks are considered: Type I truck has low capacity, is the fastest and emits less carbon emission than Type II truck. The Type II truck has a greater capacity. The details of the other parameters of the case are provided in the appendix (refer to Tables 6–11). These tables present the data related to transportation cost, fixed cost, environment emissions, fixed emissions cost, operational cost, discount offered, capacity of facilities and demand of each customer zone.

To apply the LP-metrics method, the optimum value of each objective is required which is calculated by optimising each objective separately. Thus, the three models can be considered as follows: Model 1 minimizes the total cost of the network, while Model 2 minimizes the total emissions and Model 3 considers both objectives simultaneously to obtain the optimum value. These three models are coded in MS-Excel and the Solver is used to obtain the optimal solution.

Case 1 considers the demand of 10 000 kg tomatoes in the Raipur market. The ratio of demand of the online channel (direct shipment) to BOPS to retail outlets is 20-20-60, respectively, which indicates that the online channel demand is 20% of the total demand, BOPS demand is 20% and retail outlets channel demand counts for 60%. Table 4 shows the value of 10 different scenarios and the resulting optimal solutions for the three objectives by varying the different weights w_1 and w_2. When $w_1 = 1$ and$w_2 = 0$, model 3 is changed into model 1, while in case of $w_1 = 0$ and$w_2 = 1$, model 3 becomes similar to model 2. The minimum value for the cost objective i.e., 62098, is observed for$w_1 = 1$and$w_2 = 0$. Opposed to these results, the total emissions and the delivery time are both minimal when$w_2 = 0$ and$w_2 = 1$, with values equal to 4978.78 Kg CO2 and 44.64 h, respectively. When the weight of the emissions objective decreases, the optimal values of the emissions increase but smoothly, until a value of$w_2 = 0.1$. Between the values 0.1 and 0.9, there exist a range of weights, where the objective function representing the CO2 emissions is not very sensitive. In addition, the optimal configurations along the range of weights are the same. Indeed, except for Scenario 10 where $w_1 = 1$ and$w_2 = 0$, in all other scenarios, a maximum of two collection centers, one pickup point and three retail outlets need to be open to serve the customers. The scenario 10 representing the extreme situation, when only the cost objective function is considered in the optimisation process, suggests an optimal configuration in which an additional pickup point must be open.

The case 2 studies the effect of demand on various channels. For this purpose, 18 different instances have been simulated and analysed. Each channel demand is increased in steps of 20%, while the remaining demand is equally considered between the other two channels. For example, scenario 2 with a demand ratio 20-40-40, describes that the online channel demand is 20% of total demand and the remaining 80% of the demand is equally distributed between BOPS and retail outlets channel. Here, under each scenario, 10 more scenarios may be considered as in Table 4, however, fore simplicity reasons, we have shown only the equal weight scenario, where $w_1 = 0.5$ and$w_2 = 0.5$ since that we have shown that in this range, the solution is not very sensitive and could be considered as representative of the optimal solution. Table 5 shows the value of each of the three objectives, the number of collection

Table 11
Data from collection center to retail outlet and capacity, fixed cost, and fixed emission of retail outlet.

	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10
Pathalgaon	4.1/0.328/6.1	4.15/0.332/6.2	4.15/0.332/6.2	4.15/0.332/6.2	4.1/0.328/6.1	4.2/0.336/6.3	4.1/0.3328/6.2	4.1/0.328/6.1	4.15/0.332/6.2	4.1/0.328/6.1
Pharsabahar	4.8/0.432/8.2	4.75/0.404/8	4.78/0.406/8.1	4.75/0.404/8	4.8/0.432/8.2	4.8/0.432/8.2	4.8/0.432/8.2	4.72/0.401/7.9	4.72/0.401/7.9	4.82/0.434/8.2
Kansabel	4.428/0.376/6.9	4.43/0.377/6.9	4.43/0.377/6.9	4.428/0.376/6.9	4.428/0.376/6.9	4.428/0.376/6.9	4.4/0.352/6.9	4.385/0.351/6.9	4.4/0.352/6.9	4.4/0.352/6.9
Duldula	5.292/0.476/8.9	5.3/0.477/8.9	5.3/0.477/8.9	5.25/0.472/8.7	5.25/0.472/8.7	5.155/0.464/8.5	5.25/0.472/8.7	5.25/0.472/8.7	5.3/0.447/8.9	5.4/0.459/9
Capacity (in Kg.)	2000	2200	800	1200	1000	1200	800	800	2000	2000
FC/FE	80/8	85/9	70/7.2	85/9	80/8	85/9	70/7.2	70/7.2	80/8	80/8

centers, the pickup points and the retail outlets to be opened to serve the customers and fulfil their demand.

Fig. 2 and Fig. 3 show the variation of the economic costs and the environmental emissions against the demand ratio, which varies from 0 to 1, respectively. The weights are varied to determine the impact of each sustainable objective on the distribution network while the demand between the various channels is varied to identify the impact and the performance of each distribution channel.

As the online or BOPS demand increases, the economic cost and carbon emissions both decrease, underlining the case organisation's need to plan for future expansion in e-commerce. The organisation could also restructure their existing facilities to respond to the expected increase in e-commerce, due to the increased availability of online ordering and e-commerce platforms. The results also show that the total cost of BOPS is lower than the online direct shipment strategy for a demand ratio below 60%, surpassing it thereafter. This could be explained by the increase in physical infrastructure for storage of the goods, which incurs additional fixed and operational costs. On the other hand, the carbon emissions for BOPS are above that of the online direct shipment strategy for a demand ratio below 35%, inversing as the demand ratio increases. This is explained by the fixed and operational emissions from the BOPS physical infrastructure at a lower demand ratio, which is surpassed by the emissions for the direct shipments as the demand ratio increases. Furthermore, as we move more towards online channels, operational costs decrease thanks to reduced inventory levels and total cost. Although, moving towards online channels has advantages, disadvantages may also exist, and retailers need to decide their optimal strategy based on the requirements of their market conditions, however this falls outside of the scope of this paper.

6. Conclusion

The agro-food industry is being confronted with dramatically changing consumer distribution preferences amid the COVID-19 pandemic. In addition, the recent farm's law passed by the Indian government, which allows farmers to sell their produce on the open market, has generated an opportunity in the AFSC to design a distribution network that supports sustainable online fresh food retailing in the Indian context. To this effect, the present work is an effort to design a multi-channel distribution network that captures the changing preferences of consumers in the post COVID-19 scenario. Three types of shipment strategies are considered: direct shipping (through online trading), buy online pickup in store (BOPS) and in-store purchasing. The applicability of the proposed model is demonstrated on a tomato AFSC in India and solved using an integrated ε-constraint and LP-metric approach. Furthermore, a sensitivity analysis is carried out by varying the weights of the sustainability objectives and varying the demand ratios of each distribution channel. The results reveal that as the demand of direct online shipping and BOPS increases, both the economic costs and carbon emissions are reduced, while the reverse is observed for in-store purchasing. As the online direct shipping and BOPS distribution channels are expected to accelerate in growth in the post-COVID period, the AFSC retailers are encouraged to focus on providing the option of multi-channel distribution to their consumers. In India, the government ought to establish an online channel or use the existing APMC and electronic National Agriculture Market (e-NAM) structure to allow farmers to provide better prices for produce. Thus, the role of government is crucial to provide both a physical and digital infrastructure who could even charge a nominal fee to use of their platforms. Providing such an infrastructure and supporting policies may aid in fulfilling the Government's agenda of doubling the farmers' incomes.

This work has some limitations that will be addressed in future research works. In fact, the multi-objective model proposed in the paper is solved using classical optimisation techniques since the real-problem size considered is relatively small. However, this might not be the case if the problem size increases. In such case, both methods and solving approaches could be improved where heuristics should be developed and applied. The model could also be extended to multi-produce and multi-time horizon settings to address real-life problems, for which local Indian policy makers needs to design optimal distribution networks. Moreover, since the problem does not include time dependant factors representing perishability issues, in future studies, food loss, and quality decay will be considered in the description of the model to resemble with various real-world situations.

CRediT authorship contribution statement

Vinay Surendra Yadav: Investigation, Methodology, Validation, Writing - original draft. **A. R. Singh:** Conceptualization, Formal analysis, Validation, Supervision. **Rakesh D. Raut:** Conceptualization, Methodology, Supervision. **Naoufel Cheikhrouhou:** Methodology, Visualization, Writing - review & editing.

Declaration of Competing Interest

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

Appendix

Note:

1. P1 to P6 are the pickup point. R1 to R10 are the retail outlets. The 20 customer zones include D1 to D10 and R1 to R10. FC is fixed cost (in Rupees) and FE is fixed emission (in CO_2 Kg.).
2. The values are written in the form of (transportation cost per Kg. (in Rupees)/carbon emission per Kg. (in CO_2 Kg.)/time (in hours).
3. The per Kg. operational cost at collection center, pickup point and retail outlet is 1.2, 0.6 and 0.7 Rupees respectively while per Kg. fixed emission is 0.1, 0.05 and 0.06 CO_2 Kg. respectively.

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