

Modelling of the sustainable food grain supply chain distribution system: a bi-objective approach

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Abstract: Growing food demand, environmental degradation, post-harvest losses and the dearth of resources encourage the decision makers from developing nations to integrate the economic and environmental aspects in food supply chain network design. This paper aims to develop a bi-objective decision support model for sustainable food grain supply chain distribution system considering an entire network of procurement centres, central, state and district level warehouses, and fair price shops. The model seeks to minimize the cost and carbon dioxide emission simultaneously. The model covers several problem peculiarities such as multi-echelon, multi-period, multi-modal transportation, emission caused due to various motives, heterogeneous capacitated vehicles and limited availability, multiple sourcing and distribution, and capacitated warehouses. Several different realistic problem instances are solved using the two Pareto based multi-objective algorithms. Sensitivity analysis results imply that the decision makers should establish the sufficient number of warehouses in each producing and consuming states by maintaining the suitable balance between the two objectives. Multiple policymakers like Food Corporation of India, logistics providers and state government agencies will be benefited from this research study.

Keywords: Food supply chain; Sustainable supply chain; Facility location; Transportation; Modelling and optimization

1. Introduction

1.1 Background

Global food demand is estimated to increase by 50% by 2030 which leads to upsurge the demand of resources for producing and transporting it (Allaoui et al. 2018, Bruinsma 2017). According to the estimation of the Food and Agricultural Organization (FAO), nearly 1.3 billion tons of food produced worldwide is wasted or lost annually (Gustavsson et al. 2011; FAO 2013). The food production in India has been steadily augmented thanks to advanced agricultural production technologies, but the food losses are still one of the major issues (Sharon et al. 2014; Kumar and Kalita 2017; Parwez 2014). Approximately 30-35% of total food produced is wasted annually because of insufficient infrastructure and ineffectual supply chain (Parwez 2014; Comptroller and Auditor General of India (CAG) report 2013). Various inputs containing land, water, pesticides, fertilizer, and energy are required for producing food. The process leads to the production of greenhouse gas emissions. Therefore, wastages of resources and production of emissions are two main consequences of food losses (FAO 2013; Zhu et al. 2018). Additionally, food loss is one of the major causes of significant environmental impact along with economic and social impacts (Dreyer et al. 2019; Lemaire and Limbourg 2019; Scholz et al. 2015).

Transportation planning plays a crucial role in the overall costs of any supply chain (Maiyar and Thakkar 2017; Song et al. 2014). India comes third after the China and US in the largest

global greenhouse gases emitter ranking (Timperley 2019). Also, transportation activities are the major causes of air pollution which have harmful effects on human health (Kelle 2019; Wang et al. 2011). Globally freight transport typically contributes 80-90% for transportation-related carbon-emission (McKinnon 2010). In 2018, transportation activities emitted 24% of world's annual carbon dioxide (Teter et al. 2019). Road transportation emission is the major contributor (94.5%) for India's total transport sector emission of 261 tons of CO₂ (Shrivastava et al. 2013). Further, agricultural sector has the share of 16% in total greenhouse gas emissions (Timperley 2019). The crop yield in India is considerably reduced because of the heightened air pollution and climatic factors (Burney and Ramanathan 2014). Therein, approximately 5 million tons of crops (wheat and rice) get damaged annually due to pollutant gases (Ramanathan et al. 2014). According to the report of the Lancet Commission on pollution and health, India has ranked at first position in pollution-related deaths (2.51 million deaths in 2015) (Landrigan et al. 2018). Therefore, consideration of the environmental impact of Food Supply Chain (FSC) activities along with economic objective is very imperative and it increases the problem complexity (Banasik et al. 2019; Mohammed and Wang 2017b; Seuring 2013; Brandenburg et al. 2014; Wang et al. 2019).

1.2 Indian food grain supply chain distribution system

This study is related to the food grain supply chain of Public Distribution System (PDS) in India as shown in Figure 1. Under the PDS, the Food Corporation of India (FCI) distributes the subsidized food grains to the weaker and vulnerable section of the society (CAG, 2013; Mogale et al. 2017). Procurement from farmers, storage, transportation and distribution to final consumers through Fair Price Shops (FPS) are the major activities of FCI (Maiyar et al. 2015). Due to the mismatch between the supply and demand of particular states, food grain has to be transferred from producing (surplus) states to consuming (deficit) states (Maiyar and Thakkar 2017; Mogale et al. 2017; Mahapatra and Mahanty 2018; Balani et al. 2013). The major wheat

producing and consuming states in India are situated in a large geographically dispersed area which results in more fuel consumption for food grain transportation (Reddy et al. 2017; Anoop et al. 2018, High level committee report (HLC) 2015). The food grain is transported from surplus to deficit states through rail mode to meet the demand of the peoples (HLC 2015; CAG 2013; Maiyar et al. 2015; Balani et al. 2013).

<<< Insert Figure 1 here >>>

1.3 Motivations

The key motivations behind the current study including food grain storage problems and improper planning and coordination issues are realized from the report of the CAG report (2013), HLC report (2015) and online sources (www.indiastat.com). According to these sources, the total food grains stock in central pool has progressively augmented from 21 Million Metric Ton (MMT) in 2007 to 55.4 MMT in 2017, whereas FCI has increased its owned storage capacity by merely 0.2 Million Metric Ton (MMT) (15.2 – 15.4 MMT) in the period from 2006-07 to 2016-17. The shortfall in storage capacity with FCI against the required capacity indicates an increasing trend from 5.995 MMT in 2007-08 to 19.37 MMT in 2016-17. These statistics indicate the discrepancy between the available storage capacity and central pool stock and emphasize the requirement of more storage capacity to deal with escalating procurement. Furthermore, CAG report revealed severe disparities in the availability of storage capacity and a colossal dearth of storage space in deficit states. The abrupt augmentation of food grains stock in central pool impels the concern of larger movement from producing to consuming states. In order to bridge the storage capacity gap, policymakers in India is establishing the heterogeneous capacitated warehouses in producing and consuming states. Annually, on an average of 40 to 42 million tons of food grains are transferred across the country using a road, rail, and waterways (<http://fci.gov.in>). According to the CAG 2013 report,

the total number of 10,969 rakes are dispatched for food grain movement during the period of 2011-12. Managing the food supply chain is an intricate and difficult issue since the number of intermediaries may differ from a commodity to another and to a country to another (Sachan et al. 2005; Higgins et al. 2010; Piramuthu et al. 2013). The post-harvest activities including transportation, processing, and storage are responsible for producing emissions (Allaoui et al. 2018; Banasik et al. 2019; FAO, 2013).

1.4 Major contributions

The main contributions of this paper are as follows. Firstly, a new bi-objective mathematical model is formulated for integrated sustainable food grain supply chain distribution system considering an entire network of procurement centres, central, state and district level warehouses, and fair price shops. The objectives of the model are minimization cost and carbon dioxide emissions. Moreover, the model introduces several practical and realistic features of the problem like multiple echelons, periods, transportation modes, sourcing and distribution along with heterogeneous capacitated vehicles and their limited availability. Transportation emissions affected by vehicle types, load of vehicles and travelled distances, emission caused due to facility establishment, holding and handling operations are also incorporated in the proposed model. Additional characteristics such as geographically dispersed producing and consuming states, capacitated warehouses and vehicle capacity restrictions are integrated in the model. The developed model supports the policymakers for strategic and tactical planning decisions by optimizing the facility establishments, inventory level, and food grain flow from procurement centres to fair price shops. Furthermore, several trade-off solutions are obtained by solving the model using two Pareto based multi-objective algorithms comprising of Multi-objective Particle Swarm Optimization (MOPSO) and Non-Dominated Sorting Genetic Algorithm (NSGA-II).

1.5 Structure of the paper

The remainder of the paper is organized in the following way. In Section 2, relevant literature is discussed. Section 3 presents the underline problem description. The formulation of the mathematical model is described in Section 4. In Section 5, the research methodology is explained. Section 6 is devoted to the results and discussion. Finally, concluding remarks and future scope is given in Section 7.

2. Review of relevant literature

Recently, an interesting and insightful mathematical model oriented review of the extant literature focusing on Sustainable Food Supply Chain (SFSC) domain was conducted by Estes et al. (2018) and Zhu et al. (2018). They clearly highlighted the need of the development of mathematical programming models to support the decision making process of FSC in developing countries. The different challenges starting from farmers to consumers, recent trends and topics in food supply chains, configuration of food supply chains, need of sustainability, integration of the inherent characteristics and network of FSC are discussed in these two papers. They also found that most of the previous authors considered the generic FSC and not explored all the entities involved in it. The necessity of multiple time periods, integration of procurement, transportation and storage decisions, economic and environmental aspects and their conflicting nature, multi-objective modelling and algorithms/heuristics applications are delineated in these two papers. In addition to this, interested readers can confer the Soto-Silva et al. (2016), Ahumada and Villalobos (2009), Brandenburg and Rebs (2015), Dekker et al., (2012), Demir et al. (2014) and Eskandarpour et al. (2015) for literature review on sustainable supply chain network design and green logistics related aspects. In this section, the relevant literature concentrating on integrated sustainable facility location inventory transportation problem in the FSC domain is discussed. Therein, we mainly focused on various

types of models and their characteristics available in the literature and different solution approaches reported.

In recent times, a sustainable agro-food supply chain network design problem was addressed by Allaoui et al. (2018) through an integrated two-stage hybrid approach. Mohammed and Wang (2017a) simultaneously minimized the transportation cost, required transportation vehicles and delivery time in meat supply chain. The authors extended their research with consideration of transportation cost, environmental impact, average delivery time and distribution time (Mohammed and Wang 2017b). They suggested a few extensions of their study by integrating the multi-period, multi-echelon and multi-objective metaheuristic algorithms. The sustainability in closed-loop supply chain problems can be seen in Banasik et al. (2017), Hasani et al. (2012) and Nurjanni et al. (2017) studies. Kaur and Singh (2017) proposed a joint sustainable procurement and logistics model considering the emission generated during ordering, holding and logistics.

Some researchers considered the sustainability in the various forms while examining the several FSC problems like two-layer supply chain network design (Validi et al. 2014a, 2015), location-routing (Validi et al. 2018; Govindan et al. 2014), fresh food distribution (Bortolini et al. 2018) and beef/meat logistics network (Soysal et al. 2014, Golini et al. 2017). Majority of these studies have not simultaneously explored various practical features of food supply chain problems related to multi-period, heterogeneous capacitated vehicles and their limited availability, multiple sourcing, multi-modal transportation, capacitated warehouses, CO₂ emission produced due to different reasons, and vehicle capacity constraints. The food quality and sustainability indicators were integrated into discrete event simulation models for an analysis of an integrated approach in the FSC (Van Der Vorst et al. 2009). The metaheuristic approach was suggested for resilient FSC design problem (Bottani et al. 2019). Furthermore, a decision support system was recommended for sales forecasting and order planning operations

of fresh FSC (Dellino et al. 2017). The remaining shelf-life of the perishable food was predicted by means of data collected through the sensor network (Li and Wang 2017). A carbon trading mechanism in fresh FSC was introduced by Wang et al. (2018). The overview of key relevant papers delineating the main features of the model, components of two objective function, decisions taken and the solution methods used are mentioned in Table A.1 in appendix A.

It can be noticed from Table A.1 that most of the authors modelled the problem in the form of MILP or MIP considering the multi-echelon scenario. However, multiple time periods and transportation modes were considered in limited studies. In the case of total cost objective, facility location cost and variable transportation cost were largely taken into account by several researchers. Fixed transportation, inventory and handling costs appeared in fewer number of papers. Almost all authors mentioned in Table A.1 incorporated the transportation CO₂ emission and few researchers included the CO₂ emission generated due to facility establishment, inventory holding and handling activities. Determination of location along with product flows were mostly addressed decisions in extant literature and heterogeneous fleet utilized and inventory level were observed in limited number of research works. Limited number of scholars contributed to food distribution network design regardless of its huge significance (Meneghetti and Monti 2015). The SFSC is considered a very contextual because of the variability of food system in various countries (Zhu et al. 2018, Maiyar and Thakkar et al. 2017). There are several factors behind this variability like supply chain actors, different procurement periods, transportation and storage systems and geographically widespread producing and consuming provinces. The involvement of heterogeneous actors and their complex collaborations make the grain supply chain system more complex and dynamic (Swaminathan et al., 1998; Simonson, 2009). Indian food grain distribution system is the world's largest distribution system of its kind and different as well as unique as compared with other developing nations (Balani et al. 2013). Furthermore, managing this system becomes

more intricate and difficult issue as compared to developed economies due to its chaotic nature and a large number of intermediaries (Sachan et al., 2005).

3. Problem statement

The shortfall in storage capacity with FCI can be observed from the statistical data mentioned in subsection 1.3 motivation. The policymakers in India are establishing the capacitated warehouses in several geographically dispersed surplus and deficit states to bridge the storage capacity gap. The warehouse establishment decision comes under the strategic category and requires a large amount of initial investment for establishment based on its capacity levels. In order to curb the CO₂ emission generated due to the travelling of larger distances, more number of warehouses will be required, i.e. large investment and vice-versa. In addition to this, the trade-off occurs between the transportation cost and transportation CO₂ emission due to the fixed hiring cost and emission produced by heterogeneous capacitated vehicles. It means that lower emission from transportation comes at a higher cost. Thus, we have developed a bi-objective mathematical model which seeks to minimize the cost and emission simultaneously. The main goal here is to decide on the locations and on the movement and storage planning in a multi-period environment. The following decision variables are considered (1) location of central, state and district level warehouses (2) optimal quantity of food grain to be moved from procurement centres to fair price shops, (3) inventory available in the central, state and district level warehouses at the end of period, and (4) optimal number of heterogeneous capacitated vehicles used for food grain transportation.

4. Problem formulation

Several assumptions are considered in the formulation of the problem.

- The procurement, demand and storage capacity of central, state and district level warehouses are known and deterministic.

- Potential locations of central, state and district level warehouses are known and fixed.
- The quantity of food grain procured is sufficient to meet the demand of fair price shops.
- Each fair price shops demand should be satisfied during the given time period.
Shortages and backlogs are not permitted.
- Three heterogeneous capacitated vehicles with limited availability at each echelon in each time period are available.
- Each vehicle carries Full Truck Load (FTL) transport.

Notations

Indices	Description
p	Index for procurement centres, $p = 1, 2, \dots, P$
q	Index for potential central warehouses in surplus states, $q = 1, 2, \dots, Q$
r	Index for potential state warehouses in deficit states, $r = 1, 2, \dots, R$
s	Index for potential district level warehouses, $s = 1, 2, \dots, S$
f	Index for fair price shops, $f = 1, 2, \dots, F$
k	Index for truck types available at procurement centres and state warehouse, $k = 1, 2, \dots, K$
l	Index for rake types available at central warehouse in surplus state $l = 1, 2, \dots, L$
m	Index for truck types available at district level warehouse, $m = 1, 2, \dots, M$
t	Index for time period, $t = 1, 2, \dots, T$

Parameters	Description
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fc_q	Fixed cost of establishing a central warehouse q
fc_r	Fixed cost of establishing a state warehouse r
fc_s	Fixed cost of establishing a district level warehouse s
e_k	Fixed cost of hiring a truck of type k for transportation
e_l	Fixed cost of hiring a rake of type l for transportation
e_m	Fixed cost of hiring a truck of type m for transportation
v	Unit variable transportation cost per km by road mode
u	Unit variable transportation cost per km by rail mode
ic_q	Unit inventory carrying cost per period in central warehouse q
ic_r	Unit inventory carrying cost per period in state warehouse r
ic_s	Unit inventory carrying cost per period in district level warehouse s
hc_q	Unit variable cost for handling one ton of food grain in the central warehouse q
hc_r	Unit variable cost for handling one ton of food grain in state warehouse q
hc_s	Unit variable cost for handling one ton of food grain in the district level warehouse s
g_{pq}	Distance between procurement centres p to central warehouses q
g_{qr}	Distance between central warehouses q to state warehouse r
g_{rs}	Distance between state warehouse r to district level warehouse s

g_{sf}	Distance between district level warehouse s to fair price shops f
a_p^t	Amount of grain stock available at procurement centre p during time period t
b_q	Maximum storage capacity of the central warehouse q
b_r	Maximum storage capacity of the state warehouse r
b_s	Maximum storage capacity of the district level warehouse s
d_f^t	Demand of fair price shop f during time period t
α_{kp}^t	Total number of k type of trucks available at procurement centre p in time period t
α_{kr}^t	Total number of k type of trucks available at state warehouse r in time period t
α_{lq}^t	Total number of l type of rakes available at central warehouse q in time period t
α_{ms}^t	Total number of m type of trucks available at district level warehouse s in time period t
Ω_k	Capacity of truck of type k
Ω_l	Capacity of rake of type l
Ω_m	Capacity of truck of type m
ω_q	Amount of CO ₂ released while establishing central warehouse q
ω_r	Amount of CO ₂ released while establishing state warehouse r

ω_s	Amount of CO ₂ released while establishing district level warehouse s
ω_{pq}^k	Amount of CO ₂ released per unit distance for each k type of truck travelling from procurement centre p to central warehouse q
ω_{qr}^l	Amount of CO ₂ released per unit distance for each l type of rake travelling from central warehouse q to state warehouse r
ω_{rs}^k	Amount of CO ₂ released per unit distance for each k type of truck travelling from state warehouse r to district level warehouse s
ω_{sf}^m	Amount of CO ₂ released per unit distance for each m type of truck travelling from district level warehouse s to fair price shop f
δ_q	Amount of CO ₂ released while handling one ton of food grain in central warehouse q
δ_r	Amount of CO ₂ released while handling one ton of food grain in state warehouse r
δ_s	Amount of CO ₂ released while handling one ton of food grain in district level warehouse s
ρ_q	Amount of CO ₂ released while holding one ton of food grain in central warehouse q
ρ_r	Amount of CO ₂ released while holding one ton of food grain in state warehouse r

ρ_s Amount of CO₂ released while holding one ton of food grain in district level warehouse s

W A sufficiently big number

Decision variables	Description
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Binary variables

X_q Equals to 1 if the central warehouse is established at location q and 0 otherwise

Y_r Equals to 1 if the state warehouse is established at location r and 0 otherwise

Z_s Equals to 1 if the district level warehouse is established at location s and 0 otherwise

Continuous variables

E_{pq}^t The amount of food grain dispatched by procurement centre p to central warehouse q in period t

G_{qr}^t The amount of food grain dispatched by central warehouse q to state warehouse r in period t

U_{rs}^t The amount of food grain dispatched by state warehouse r to district level warehouse s in period t

V_{sf}^t The amount of food grain dispatched by district level warehouse s to fair price shop f in period t

I_q^t	The amount of food grain available at central warehouse q at the end of period t
J_r^t	The amount of food grain available at state warehouse r at the end of period t
B_s^t	The amount of food grain available at district level warehouse s at the end of period t

Integer Variables

N_{pq}^{kt}	The number of k type of trucks dispatched from procurement centre p to central warehouse q in period t
N_{qr}^{lt}	The number of l type of rakes dispatched from central warehouse q to state warehouse r in period t
N_{rs}^{kt}	The number of k type of trucks dispatched from state warehouse r to district level warehouse s in period t
N_{sf}^{mt}	The number of m type of trucks dispatched from district level warehouse s to fair price shop f in period t

Objective functions:

Objective 1 = Minimization of Total Cost (TC)

$$\begin{aligned} \text{Min Obj1 (TC)} = & \text{Fixed cost of facility location} + \text{Transportation cost (fixed and variable cost)} \\ & + \text{Inventory cost} + \text{Handling cost} \end{aligned} \quad (1)$$

$$\text{Fixed cost of Facility location} = \sum_{q \in Q} fc_q X_q + \sum_{r \in R} fc_r Y_r + \sum_{s \in S} fc_s Z_s \quad (1.1)$$

Fixed transportation cost =

$$\sum_{t \in T} \sum_{k \in K} \sum_{p \in P} \sum_{q \in Q} e_k N_{pq}^{kt} + \sum_{t \in T} \sum_{l \in L} \sum_{q \in Q} \sum_{r \in R} e_l N_{qr}^{lt} + \sum_{t \in T} \sum_{k \in K} \sum_{r \in R} \sum_{s \in S} e_k N_{rs}^{kt} + \sum_{t \in T} \sum_{m \in M} \sum_{s \in S} \sum_{f \in F} e_m N_{sf}^{mt} \quad (1.2)$$

Variable transportation cost =

$$\sum_{t \in T} \sum_{p \in P} \sum_{q \in Q} v g_{pq} E_{pq}^t + \sum_{t \in T} \sum_{q \in Q} \sum_{r \in R} u g_{qr} G_{qr}^t + \sum_{t \in T} \sum_{r \in R} \sum_{s \in S} v g_{rs} U_{rs}^t + \sum_{t \in T} \sum_{s \in S} \sum_{f \in F} v g_{sf} V_{sf}^t \quad (1.3)$$

$$\text{Inventory cost} = \sum_{t \in T} \sum_{q \in Q} I_q^t ic_q + \sum_{t \in T} \sum_{r \in R} J_r^t ic_r + \sum_{t \in T} \sum_{s \in S} B_s^t ic_s \quad (1.4)$$

Handling cost =

$$\sum_{t \in T} \left[\sum_{p \in P} \sum_{q \in Q} E_{pq}^t + \sum_{q \in Q} \sum_{r \in R} G_{qr}^t \right] hc_q + \sum_{t \in T} \left[\sum_{q \in Q} \sum_{r \in R} G_{qr}^t + \sum_{r \in R} \sum_{s \in S} U_{rs}^t \right] hc_r + \sum_{t \in T} \left[\sum_{r \in R} \sum_{s \in S} U_{rs}^t + \sum_{s \in S} \sum_{f \in F} V_{sf}^t \right] hc_s \quad (1.5)$$

The calculation of emissions from various sources is the crucial stage in the model formulation. The emission factor based on the total storage capacity of the warehouses is taken into consideration while determining the emission generated because of facility establishment. We have followed the approach of fixed transportation emission per vehicle described in Paksoy et al., (2011) and Mohammed and Wang (2017b) for calculating the transportation emission. The fixed emission factor per unit stocked and handled is considered for calculating the inventory and handling related emissions (Kaur and Singh 2017; Oglethorpe, 2010).

Objective 2 = Minimization of Total Emission of CO₂ (TE)

Min Obj2 (TE) = Emission due to facility establishment + Emission due to transportation

$$+ \text{Emission due to inventory holding} + \text{Emission due to handling} \quad (2)$$

$$\text{Emission due to facility establishment (EF)} = \sum_{q \in Q} \omega_q X_q + \sum_{r \in R} \omega_r Y_r + \sum_{s \in S} \omega_s Z_s \quad (2.1)$$

Emission due to transportation (ET) =

$$\begin{aligned} & \sum_{t \in T} \sum_{k \in K} \sum_{p \in P} \sum_{q \in Q} \omega_{pq}^k g_{pq} N_{pq}^{kt} + \sum_{t \in T} \sum_{l \in L} \sum_{q \in Q} \sum_{r \in R} \omega_{qr}^l g_{qr} N_{qr}^{lt} + \sum_{t \in T} \sum_{k \in K} \sum_{r \in R} \sum_{s \in S} \omega_{rs}^k g_{rs} N_{rs}^{kt} + \\ & \sum_{t \in T} \sum_{m \in M} \sum_{s \in S} \sum_{f \in F} \omega_{sf}^m g_{sf} N_{sf}^{mt} \end{aligned} \quad (2.2)$$

Emission due to inventory holding (EI) =

$$\sum_{t \in T} \sum_{q \in Q} \rho_q I_q^t + \sum_{t \in T} \sum_{r \in R} \rho_r J_r^t + \sum_{t \in T} \sum_{s \in S} \rho_s B_s^t \quad (2.3)$$

Emission due to handling (EH) =

$$\sum_{t \in T} \left[\sum_{p \in P} \sum_{q \in Q} E_{pq}^t + \sum_{q \in Q} \sum_{r \in R} G_{qr}^t \right] \delta_q + \sum_{t \in T} \left[\sum_{q \in Q} \sum_{r \in R} G_{qr}^t + \sum_{r \in R} \sum_{s \in S} U_{rs}^t \right] \delta_r + \sum_{t \in T} \left[\sum_{r \in R} \sum_{s \in S} U_{rs}^t + \sum_{s \in S} \sum_{f \in F} V_{sf}^t \right] \delta_s \quad (2.4)$$

Subject to constraints

The total amount of food grain shipped from the procurement centre to any central warehouse should be less than or equal to the maximum quantity available at a particular procurement centre in a given time period.

$$\sum_{q \in Q} E_{pq}^t \leq A_p^t \quad \forall p, \forall t \quad (3)$$

A procurement centre has to transfer the food grain quantity to the established central warehouse only.

$$E_{pq}^t \leq WX_q \quad \forall p, \forall q, \forall t \quad (4)$$

The total amount of food grain distributed from central warehouse to any state warehouse is restricted by the maximum available inventory at the respective central warehouse in a given period t .

$$\sum_{r \in R} G_{qr}^t \leq I_q^t \quad \forall q, \forall t \quad (5)$$

Food grain from the central warehouse is transferred to the state warehouse only if both central and state warehouses are established

$$G_{qr}^t \leq WX_q Y_r \quad \forall q, \forall r, \forall t \quad (6)$$

Similarly, the supply restrictions of state warehouse and district level warehouse are represented by constraint (7) and (8) respectively.

$$\sum_{s \in S} U_{rs}^t \leq J_r^t \quad \forall r, \forall t \quad (7)$$

$$\sum_{f \in F} V_{sf}^t \leq B_s^t \quad \forall s, \forall t \quad (8)$$

Food grain from state warehouse is dispatched to district level warehouse only if both state and district level warehouses are constructed.

$$U_{rs}^t \leq WY_r Z_s \quad \forall r, \forall s, \forall t \quad (9)$$

Correspondingly, district level warehouse distributes the food grain to fair price shops only if the district level warehouse is established.

$$V_{sf}^t \leq WZ_s \quad \forall s, \forall f, \forall t \quad (10)$$

Total amount of food grain shipped from all district level warehouses should be equal to the demand of fair price shop.

$$\sum_{s \in S} V_{sf}^t = d_f^t \quad \forall f, \forall t \quad (11)$$

The inventory at central warehouse should be lower or equal to the maximum inventory holding capacity of the central warehouse at any time.

$$I_q^{(t-1)} + \sum_{p \in P} E_{pq}^t \leq b_q^t \quad \forall q, \forall t \quad (12)$$

Similarly, the capacity constraints of state warehouse and district level warehouse are defined by the constraint (13) and (14) respectively.

$$J_r^{(t-1)} + \sum_{q \in Q} G_{qr}^t \leq b_r^t \quad \forall r, \forall t \quad (13)$$

$$B_s^{(t-1)} + \sum_{r \in R} U_{rs}^t \leq b_s^t \quad \forall s, \forall t \quad (14)$$

Inventory flow balance equations for central warehouses, state warehouses and district level warehouses are illustrated by Constraints (15), (16) and (17) respectively.

$$I_q^{(t-1)} + \sum_{p \in P} E_{pq}^t - \sum_{r \in R} G_{qr}^t = I_q^t \quad \forall q, \forall t \quad (15)$$

$$J_r^{(t-1)} + \sum_{q \in Q} G_{qr}^t - \sum_{s \in S} U_{rs}^t = J_r^t \quad \forall r, \forall t \quad (16)$$

$$B_s^{(t-1)} + \sum_{r \in R} U_{rs}^t - \sum_{f \in F} V_{sf}^t = B_s^t \quad \forall s, \forall t \quad (17)$$

Total amount of food grain quantity dispatched from procurement centre to central warehouse has to be lower or equal to the total capacity of trucks shipped between the same echelons.

$$E_{pq}^t \leq \sum_{k \in K} N_{pq}^{kt} \Omega_k \quad \forall p, \forall q, \forall t \quad (18)$$

Correspondingly, the rake capacity constraint between a central and state warehouse, truck capacity constraint between state and district level warehouse, and truck capacity constraint

between district level warehouse and fair price shop are specified by constraint (19), (20) and (21) respectively.

$$G_{qr}^t \leq \sum_{l \in L} N_{qr}^{lt} \Omega_l \quad \forall q, \forall r, \forall t \quad (19)$$

$$U_{rs}^t \leq \sum_{k \in K} N_{rs}^{kt} \Omega_k \quad \forall r, \forall s, \forall t \quad (20)$$

$$V_{sf}^t \leq \sum_{m \in M} N_{sf}^{mt} \Omega_m \quad \forall s, \forall f, \forall t \quad (21)$$

The number of each type of trucks utilized from the procurement centre to central warehouse should be within the maximum trucks available at respective procurement centre at a given time period.

$$\sum_{q \in Q} N_{pq}^{kt} \leq \alpha_{kp}^t \quad \forall p, \forall k, \forall t \quad (22)$$

Likewise, the restrictions on a number of rakes used between central and state warehouse, the number of trucks shipped from state to district level warehouse, and the number of trucks moved from district level warehouse to fair price shops are described using Constraint (23), (24) and (25) respectively.

$$\sum_{r \in R} N_{qr}^{lt} \leq \alpha_{lq}^t \quad \forall q, \forall l, \forall t \quad (23)$$

$$\sum_{s \in S} N_{rs}^{kt} \leq \alpha_{kr}^t \quad \forall r, \forall k, \forall t \quad (24)$$

$$\sum_{f \in F} N_{sf}^{mt} \leq \alpha_{ms}^t \quad \forall s, \forall m, \forall t \quad (25)$$

Binary decision variables which indicate the establishment of central, state and district level warehouses.

$$X_q, Y_r, Z_s \in \{0,1\} \quad \forall q, \forall r, \forall s \quad (26)$$

The total amount of food grain quantity dispatched from a procurement centre to a central warehouse, a central warehouse to state warehouse, a state warehouse to a district level warehouse and a district level warehouse to fair price shop should be higher or equal to zero. Also, the inventory available at central warehouse, state warehouse, and district level warehouse should be higher or equal to zero.

$$E'_{pq}, G'_{qr}, U'_{rs}, V'_{sf}, I'_q, J'_r, B'_s \geq 0 \quad \forall p, \forall q, \forall r, \forall s, \forall f, \forall t \quad (27)$$

Total number of each type of vehicle travelled from a procurement centre to a central warehouse, a central warehouse to state warehouse, a state warehouse to a district level warehouse and a district level warehouse to fair price shops should be an integer.

$$N^{kt}_{pq}, N^{lt}_{qr}, N^{kt}_{rs}, N^{mt}_{sf} \in \mathbb{Z}^+ \quad \forall p, \forall q, \forall r, \forall s, \forall f, \forall k, \forall l, \forall m, \forall t \quad (28)$$

5. Research methodology

Due to the conflicting nature of the two objectives, there is a need to find out the set of Pareto optimal solutions of the proposed model (Musavi and Bozorgi-Amiri 2017). The classical multi-objective methods including epsilon constraint, goal programming, and weighted sum methods take substantial computational time for solving the real size problem instances because of a large set of variables and constraints (Kadambala et al. 2017; Maiyar and Thakkar 2017; Yu et al. 2017). Moreover, these techniques generate only one optimal point on the Pareto frontier in a single iteration, which lacks credibility in decision making (Pasandideh et al. 2015; Deb, 2001). In the extant literature, several authors have proved the efficiency and effectiveness of MOPSO and NSGA-II algorithms in dealing with bi-objective and multi-objective problems. Indeed, complex multi-objective problems including series-parallel inventory redundancy allocation problem (Alikar et al. 2017), low-carbon distribution system problem (Validi et al. 2014b), cross-docking scheduling problem (Mohtashami et al. 2015) and

inventory control problem (Mousavi et al. 2016; Srivastav and Agrawal 2016) are tackled through MOPSO and NSGA-II algorithms. The MOPSO is used due to its ease of execution, the capability of endowing good convergence and preserving a balance between exploitation and exploration (Chakraborty et al. 2011; De et al. 2017; Govindan et al. 2019). The NSGA-II is well recognized, popular and robust algorithm to solve the multi-objective models (Pasandideh et al. 2015; Musavi and Bozorgi-Amiri 2017). Therefore, these two algorithms are implemented to obtain the Pareto optimal solutions to the problem.

The comprehensive steps of these two algorithms and data collection method are represented in the overall research methodology as shown in Figure B.1 (refer appendix B). The warehouse location-allocation problem is identified from storage capacity gap associated with the FCI. The critical review of the SFSC problems is carried out to analyse different model characteristics and find out the research gap. Next, bi-objective mathematical model that seeks to minimize cost and carbon emission is formulated to support the decision making process of policymakers. The data pertaining to model parameters is gleaned from several reliable sources. The data related to fixed cost of warehouse locations and its capacity, inventory and operational cost is obtained from the High-level committee report (2015). Vehicle related data including fixed and variable transportation costs, availability of vehicles and its capacity, supply and demand, and potential locations of warehouses are collected from field visits. The data related to amount of CO₂ released due different activities is gleaned from Nurjanni et al. (2017), Harris et al. (2014) and Mohammed and Wang (2017b) studies. The distances between the two locations are determined from the google maps. Table B.1 (appendix B) provides the summary of these model parameters values. Further, two Pareto based algorithms are selected to solve the bi-objective mathematical model and carried out the parameter tuning of algorithmic parameters. Finally, proposed algorithms are implemented and results are compared following the relevant literature.

5.1 Multi-objective particle swarm optimization (MOPSO)

A population-based optimization technique called particle swarm optimization (PSO) algorithm was proposed by Eberhart and Kennedy (1995) inspired from the behaviour of bird flocking and fish schooling. The PSO algorithm is mainly used for the optimization of single objective models and provides near-optimal solutions. Inspired by the PSO strategy, Moore and Chapman (1999) developed the MOPSO algorithm for solving multi-objective problems, where the Pareto archive is used to store all non-dominated solutions. PSO based algorithms are simple for implementation, needs less parameter setting and balanced mechanism for local and global explorations (Trelea 2003; Zheng et al. 2003). Relying on the detailed flowchart of MOPSO as given in Figure B.1, the initialization, the fast non-dominated sorting and crowding distance steps of MOPSO are similar to the NSGA-II steps. In order to update the velocity of particles, Eq. (29) and (30) are used as follows.

$$v_{t+1}^i = wv_t^i + C_1r_1(pbest_t^i - x_t^i) + C_2r_2(gbest_t^i - x_t^i) \quad (29)$$

$$x_{t+1}^i = x_t^i + v_{t+1}^i \quad (30)$$

Where v_{t+1}^i and x_{t+1}^i are the updated velocity and position vector of an i th particle in a $t+1$ iteration, r_1 and r_2 are uniformly distributed random numbers between 0 and 1, C_1 and C_2 represent the acceleration constants, $pbest$ and $gbest$ illustrates the local best for each individual and global best of the population and w is the inertia weight. Similar to the NSGA-II, parents and offspring are combined. [The algorithm stops when it satisfies the termination criteria of a maximum number of iterations.](#)

5.2 Non-Dominated Sorting Genetic algorithm II (NSGA-II)

Deb et al. (2002) proposed NSGA-II as one of the well-known and efficient Pareto based multi-objective algorithms. Several researchers have proved its effectiveness and quality by tackling

complex engineering and combinatorial multi-objective problems through NSGA-II (Govindan et al. 2014; Kadambala et al. 2017; Mohtashami et al. 2015). The problem is solved using the NSGA-II through the implementation of the several key steps mentioned in Figure B.1. The full explanation of NSGA-II algorithm is provided in the Appendix C.

6. Experimental results and discussion

Initially, fifteen problem instances are generated following the collected secondary data for verification and validation of the model. The problem characteristics include the number of procurement centres (PC), central warehouses (CW), state warehouses (SW) and district-level warehouses (DLW), fair price shops (FPS) and time periods (TP). These test problems are classified in three sizes: small, medium and large scale according to [Table D.1](#) (appendix C). Moreover, the complexity of the model in terms of a number of decision variables and constraints in each test problem is presented in the same table.

Parameter setting of the algorithm is one of the crucial aspects. The solution quality and convergence velocity mostly depend on it (Mousavi et al. 2016; Kadambala et al. 2017). Therefore, several preliminary computational experiments are performed to find out suitable parameters. The tuned algorithm parameters of NSGA-II algorithm are as follows: (1) Population size = 50; (2) crossover probability = 0.9; (3) mutation probability = 0.1 and (4) number of generations = 200. Similarly, we have set the following suitable parameters for MOPSO algorithm. (1) Swarm size = 50; (2) Inertia weight = 0.9; (3) Cognition acceleration parameter = 0.1; (4) Social acceleration parameter = 0.95 and (5) number of generations = 200.

6.1 Computational results and discussion

The Matlab (R2014a) software is used for computer coding of both algorithms. All computational experiments are run on a computer with Intel Core i5, 2.90 GHz processor with 8 GB RAM. Each problem instance is solved by means of MOPSO and NSGA-II algorithm

with calibrated parameters. The obtained solutions of the model in terms of “minimum”, “intermediate”, and “maximum” values of the first objective (total cost) and the second objective function (total CO₂ emission) along with the computational time for all instances using MOPSO and NSGA-II are reported in Tables 1 (a) and (b) respectively. The “minimum” and “maximum” portrays the highest and lowest values of a particular objective in the Pareto front. Both the objectives are treated in the same way and given the equal importance (weights) while selecting the Pareto optimal solution (intermediate) among the set of non-dominated solutions. The Pareto optimal solution mentioned in Tables 1 (a) and (b) is one among the set of Pareto solutions obtained in several runs. It can be observed from these tables that MOPSO algorithm performs better compared to NSGA-II for all considered problem instances. The CPU time taken by the NSGA-II algorithm to solve each problem instance is higher than the MOPSO. [These results supports the findings of the Kadambala et al., \(2017\), Maghsoudlou et al. \(2016\) and Srivastav and Agrawal \(2016\).](#) The cost minimal and emission minimal solution pertaining to the first problem instance is evaluated and [reported in Table 2.](#) It can be noticed from this table that if decision makers aspire to optimize the cost over the emission, the best choice has a cost value of 52.89 and emission value of 338.59. In another case, if policymakers wish to optimize emission over the cost then the values mentioned in the second row of Table 2 will be the best alternative. Finally, if there is no priority among the two objectives, an intermediate (best compromise) solution reported in the last row of Table 2 will be the best option.

<<< Insert Tables 1 (a) and (b) here >>>

<<< Insert Table 2 here >>>

One test instance from each problem category is selected to ensure conciseness in addressing the results of the optimization model. Figures 2(a) - (c) portray the Pareto frontier of both

optimization techniques for the chosen first problem instance. MOPSO provides suitable Pareto solutions with more number of Pareto points on the efficient frontier compared to NSGA-II. These Pareto points will be beneficial to the policymakers while designing the SFSC network. According to the policymaker's preferences, they can select any one solution from the set of Pareto optimal solutions. In the literature, Harris et al. (2014); Nurjanni et al. (2017); Soysal et al. (2014); Validi et al. (2014b), Guo et al. (2018) and Wang et al. (2011) discussed the similar type of solution behaviour. The nature of the obtained Pareto frontier is compatible with their results.

<<< Insert Figures 2 (a), (b) and (c) here >>>

A brief summary of all the values of decision variables considering finite planning horizon pertaining to each selected problem instance is analyzed and reported in Figures 3(a) and (b). Consolidated quantity of food grain transported between each stage and inventory available in the different warehouses at the end of the periods are represented in Figure 3(a). The carbon emission caused due transportation activities mainly depends on the vehicles dispatched for transporting food grains between echelons. Hence, Figure 3(b) illustrates the aggregated heterogeneous vehicles dispatched within a given planning period for food grains movement. The escalation in the quantity shipped between each stages and corresponding vehicles moved against the increment in the problem scale are perceived from these two figures.

<<< Insert Figures 3 (a) and (b) here >>>

6.2 Sensitivity analysis

The sensitivity analysis is conducted on the problem instance three to visualize the influence of the model parameters on each component of two objectives and to obtain more insights for

the improvement in the current SFSC. The number of procurement centres (supply) and the number of fair prices shops (demand) are two crucial parameters of the model. Therefore, these two parameters are taken into consideration to observe the impact of variation in supply and demand. Figures 4(a) and (b) depict the effect of the deviation of a number of procurement centres from -50% to +50% of its current value on cost and CO₂ emission respectively. The supply network cost is increased (35.67%) and decreased (19.33%) when the number of procurement centres increased and decreased (50%), respectively. It depicts the positive relationship between the number of procurement centres and cost. Similarly, the increment of 50% in a number of procurement centres decrease the CO₂ emission by 2.04% and decrement of 50% increases the emission by 3.52%. It means that there is a negative relationship between the procurement centres and CO₂ emission. The changes in the values of each component of two objectives can also be viewed from Figures 4(a) and (b). In a similar way, the fluctuations in the numerical values of two objectives along with their elements are reported in Figures 5(a) and (b) after varying the number of fair price shops by +50%, +25%, -25% and -50% from its original value. It is observed from figure 5(a) that total cost increased and decreased when the number of fair price shops increased and decreased. The CO₂ emission is diminished (4.65%) and increased (11.73%) after the 50% increment and reduction in a number of fair price shops. Similar to the procurement centres, fair price shops has the positive relationship with the cost and negative with CO₂ emission. These two relationship confirms conflicting nature of two objectives. Following these relationships, policymakers should focus on establishing the adequate number of warehouses in surplus and deficit states by maintaining the proper balance between two objectives. Various acronyms used in Figures 9 (a, b) and 10 (a, b) for describing the several components of cost and emission objectives are elaborated as follows. FLC - Facility location cost, TRC - Transportation cost, INC - Inventory cost, HAC - Handling cost and TC - Total cost. EFL – Emission produced during facility

establishment, ET – Transportation emission, EI – Emission generated due to the stocking of inventory, EH – Emission generated due to handling activities and TE – Total emission.

<<< Insert Figure 4 (a) and (b) here >>>

<<< Insert Figure 5 (a) and (b) here >>>

7. Conclusion and future scope

This study aimed to explore the sustainability in food supply chain domain by developing a decision support model integrating the economic and environmental dimensions. The storage capacity gap, increment of food grain stock, colossal post-harvest losses and degrading environment are some of the key motivations behind this study. The development of a bi-objective mathematical model by integrating the several problem peculiarities to support the strategic and tactical decision-making process of policymakers is the main contribution of our work. The formulated mathematical model is enough competent to demonstrate the trade-offs between cost and CO₂ emission. Small, medium and large scale problem instances stimulated from food grain supply chain in India are solved using two Pareto based multi-objective algorithms including MOPSO and NSGA-II. The solution obtained through MOPSO algorithm is superior compared with NSGA-II algorithm. Sensitivity analysis results imply that the decision makers should establish the sufficient number of warehouses in each producing and consuming states by maintaining the suitable balance between the two objectives. Some of the crucial managerial insights and theoretical implications which can improve the efficacy and effectiveness of the present food grain supply chain pertaining to the results of the study are delineated here.

7.1 Theoretical implications

This research study delivers the theoretical contributions to recent topic of sustainability in the food supply chain. Existing research work of Banasik et al. (2019), Mohammed and Wang

(2017b), Seuring (2013), Maiyar and Thakkar (2017), Brandenburg et al. (2014) and Wang et al. (2019) argued the growing attention of environmental impact of FSC activities along with the economic influence. New mathematical models are necessary to improve the food supply chain in developing nations by integrating sustainability, multiple time periods, integration of procurement, transportation and storage decisions (Esteso et al. 2018, Zhu et al. 2018). They also emphasised the integration of economic and environmental aspects and their conflicting nature and multi-objective modelling in SFSC domain. Following these arguments, a novel decision support model which aims to minimize the cost and emission is presented to design the SFSC network.

Furthermore, Past studies mainly focused on multi-echelon supply chain network with facility location and variable transportation costs and transportation emission (Banasik et al. 2017, Mohammed and Wang 2017a, 2017b, Validi et al. 2014a, 2018). Few scholars evaluated the location and transportation related decisions in their works (Musavi and Bozorgi-Amiri 2017, Govindan et al. 2014). Therefore, several practical characteristics like multiple time periods and transportation modes, heterogeneous capacitated vehicles and their limited availability, multiple sourcing and distribution, geographically dispersed producing and consuming states, capacitated warehouses and vehicle capacity restrictions are simultaneously integrated in the developed model. The transportation emissions affected by vehicle types, load of vehicles and travelled distances, emission caused due to facility establishment, holding and handling operations are also considered in the model. A comparative analysis of two meta-heuristic algorithms on the food grain supply chain problem in developing economy is also distinctive which bridges the research gap of algorithms/heuristics applications in SFSC domain (Esteso et al. 2018, Zhu et al. 2018, Validi et al. 2015, Mohammed and Wang 2017b, Allaoui et al. 2018). The influence of supply and demand uncertainty is captured through the sensitivity

analysis which overlooked in the Validi et al. (2014b) and Maiyar and Thakkar et al. (2017) studies.

7.2 Managerial implications

The different actors involved in the FSC including farmers, state government agencies of surplus and deficit states, private transporters, FCI and railways get the several insights from this research. Due to the increment of central food grain stock and gloomy capacity addition in the last decade, policy makers should bridge the storage capacity gap by establishing the adequate warehouses across the country. The proposed decision support model can be used for the feasibility analysis of the various potential locations that helps to evade the loss of huge capital investment. The establishment of central warehouses in surplus states will be helpful for quick transfer of food grain stock from procurement centres to central warehouses. This will results into the increment in the procurement from farmers and they get the benefit of MSP which improves their economic and welfare growth. Similarly, the construction of state and district level warehouses will be useful for effective distribution of food grains in deficit states and reducing the malnutrition by satisfying the demand of peoples. Due to the construction of new warehouses, farmers and other actors travel the less distances to reach the nearby warehouses. This leads to reduction of transportation cost and associated emission between different stages. The less emission will be instrumental to decrease the carbon tax of transportation activities. The emission generated by trucks is higher than the rail, hence decision makers can focus on utilization of rail rather than truck wherever possible. Therefore, transportation activities need a particular interest while establishing the warehouses. The storage losses of food grain stock by keeping it in open storage will be significantly lowered due to the establishment of new warehouses. Overall, the majority of the problems related to storage, transportation, post-harvest losses, a huge amount of hiring and carry overcharges can be resolved after the availability of sufficient storage capacity. Also, policymakers can curb the

emission produced due to central food grain stock and associated handling activities by maintaining the optimal inventory in different warehouses.

The Pareto optimal solutions obtained are helpful for the policy makers to maintain the proper trade-off between cost and carbon dioxide emission. The movement and storage activity plan in a definite planning horizon with the consideration of carbon emission can be prepared using the results of this model. Policymakers can make the various strategies and plans based on the heterogeneous capacitated vehicles movement to minimize the transportation cost and associated emission. The issues related with vehicles requirement and their scheduling along with shortages can be resolved through the time dependent movement plan of vehicles. The storage activity plan will be useful for the optimal utilization of resources.

Limitations and future scope

Similar to the other studies, the current study has few limitations which opens the door for future research opportunities. The stochastic or fuzzy multi-objective model can be formulated in the near future to capture the uncertainty in procurement and demand parameters. The present model integrated economic and environmental dimension of sustainability. We have not explored the social dimension due to the difficulty in quantifying the social factors (Esteso et al. 2018, Zhu et al. 2018). Also, water footprint needs to be incorporated in future decision support models to evaluate the impact of FSC activities on it. The current model needs the set of potential location of different warehouses for the establishment. However, in few instances, policymakers can ask the support for the determination of potential locations of warehouses. The inclusion of the minimization of lead time objective is another possible extension of the present model. The current study considered single food grain and future research can look into the multi-food grain scenario. The quantification of the post-harvest losses is another avenue for research. The proposed two metaheuristic algorithms can be applied to other problems like

location-routing, hub location and scheduling, and vehicle routing problems in crop based and animal based agro food supply chain to evaluate its effectiveness.

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References

- Ahumada, Omar, and J Rene Villalobos. 2009. "Application of Planning Models in the Agri-Food Supply Chain: A Review." *European Journal of Operational Research* 196 (1): 1–20.
- Alikar, Najmeh, Seyed Mohsen Mousavi, Raja Ariffin Raja Ghazilla, Madjid Tavana, and Ezutah Udony Olugu. 2017. "A Bi-Objective Multi-Period Series-Parallel Inventory-Redundancy Allocation Problem with Time Value of Money and Inflation Considerations." *Computers and Industrial Engineering* 104: 51–67.
- Allaoui, Hamid, Yuhan Guo, Alok Choudhary, and Jacqueline Bloemhof. 2018. "Sustainable Agro-Food Supply Chain Design Using Two-Stage Hybrid Multi-Objective Decision-Making Approach." *Computers and Operations Research* 89: 369–384.
- Anoop, K. P., Vinay V. Panicker, Manu Narayanan, and CT Sunil Kumar. 2018. "A mathematical model and solution methods for rail freight transportation planning in an Indian food grain supply chain." *Sādhanā* 43, (12): 200.
- Balani, S., 2013. *Functioning of Public Distribution System: An analytical Report* (P. L. Research, Trans.).
- Banasik, Aleksander, Argyris Kanellopoulos, G. D.H. Claassen, Jacqueline M. Bloemhof-Ruwaard, and Jack G.A.J. van der Vorst. 2017. "Closing Loops in Agricultural Supply Chains Using Multi-Objective Optimization: A Case Study of an Industrial Mushroom Supply Chain." *International Journal of Production Economics* 183: 409–420.
- Banasik, Aleksander, Argyris Kanellopoulos, Jacqueline M. Bloemhof-Ruwaard, and G. D. H. Claassen. 2019. "Accounting for uncertainty in eco-efficient agri-food supply chains: A

- case study for mushroom production planning." *Journal of cleaner production* 216: 249-256.
- Bilgen, B., and H. O. Günther. 2010. "Integrated Production and Distribution Planning in the Fast Moving Consumer Goods Industry: A Block Planning Application." *OR Spectrum* 32 (4): 927–955.
- Bortolini, Marco, Francesco Gabriele Galizia, Cristina Mora, Lucia Botti, and Michele Rosano. "Bi-objective design of fresh food supply chain networks with reusable and disposable packaging containers." *Journal of cleaner production* 184 (2018): 375-388.
- Bottani, Eleonora, Teresa Murino, Massimo Schiavo, and Renzo Akkerman. 2019. "Resilient Food Supply Chain Design: Modelling Framework and Metaheuristic Solution Approach." *Computers and Industrial Engineering* 135: 177–198.
- Brandenburg, Marcus, and Tobias Rebs. 2015. "Sustainable Supply Chain Management: A Modeling Perspective." *Annals of Operations Research* 229 (1): 213–252.
- Brandenburg, M., K. Govindan, J. Sarkis, and S. Seuring. 2014. "Quantitative Models for Sustainable Supply Chain Management: Developments and Directions." *European Journal of Operational Research* 233 (2): 299–312.
- Bruinsma, Jelle. 2017. "World agriculture: towards 2015/2030: an FAO study." *Routledge*.
- Burney, Jennifer, and V. Ramanathan. 2014 "Recent climate and air pollution impacts on Indian agriculture." *Proceedings of the National Academy of Sciences* 111 (46): 16319-16324.
- Chakraborty, Prithwish, Swagatam Das, Gourab Ghosh Roy, and Ajith Abraham. 2011. "On Convergence of the Multi-Objective Particle Swarm Optimizers." *Information Sciences* 181 (8): 1411–1425.
- De, Arijit, Alok Choudhary, and Manoj Kumar Tiwari. 2017. "Multiobjective Approach for Sustainable Ship Routing and Scheduling with Draft Restrictions." *IEEE Transactions on Engineering Management* 66 (1): 35–51.
- Deb, Kalyanmoy, Amrit Pratap, Sameer Agarwal, and T Meyarivan. 2002. "A Fast and Elitist Multiobjective Genetic Algorithm: NSGA-II." *IEEE Transactions on Evolutionary Computation* 6 (2): 182–197.
- Deb, Kalyanmoy. 2001. *Multi-objective Optimization using Evolutionary Algorithms*. John Wiley & Sons Chichester, London.
- Dekker, Rommert, Jacqueline Bloemhof, and Ioannis Mallidis. 2012. "Operations Research for Green Logistics - An Overview of Aspects, Issues, Contributions and Challenges." *European Journal of Operational Research* 219 (3): 671–679.

- Dellino, Gabriella, Teresa Laudadio, Renato Mari, Nicola Mastronardi, and Carlo Meloni. 2017. "A Reliable Decision Support System for Fresh Food Supply Chain Management." *International Journal of Production Research*: 1–28.
- Demir, Emrah, Tolga Bektaş, and Gilbert Laporte. 2014. "A Review of Recent Research on Green Road Freight Transportation." *European Journal of Operational Research* 237 (3): 775–793.
- Dreyer, Heidi C., Iskra Dukovska-Popovska, Quan Yu, and Carl Philip Hedenstierna. 2019. "A Ranking Method for Prioritising Retail Store Food Waste Based on Monetary and Environmental Impacts." *Journal of Cleaner Production* 210: 505–517.
- Eberhart, R., and J. Kennedy. "A New Optimizer Using Particle Swarm Theory." *MHS'95. Proceedings of the Sixth International Symposium on Micro Machine and Human Science*, 39–43.
- Eskandarpour, Majid, Pierre Dejax, Joe Miemczyk, and Olivier Piéton. 2015. "Sustainable Supply Chain Network Design: An Optimization-Oriented Review." *Omega* 5: 11–32.
- Esteso, Ana, M.M.E. Alemany, and Angel Ortiz. 2018. "Conceptual Framework for Designing Agri-Food Supply Chains under Uncertainty by Mathematical Programming Models." *International Journal of Production Research*: 1–29.
- FAO. 2013. "Food Wastage footprint Impacts on natural resources" *Summary Report*: 63.
- Golini, Ruggero, Antonella Moretto, Federico Caniato, Maria Caridi, and Matteo Kalchschmidt. 2017. "Developing Sustainability in the Italian Meat Supply Chain: An Empirical Investigation." *International Journal of Production Research* 55 (4): 1183–1209.
- Govindan, K., A. Jafarian, R. Khodaverdi, and K. Devika. 2014. "Two-Echelon Multiple-Vehicle Location-Routing Problem with Time Windows for Optimization of Sustainable Supply Chain Network of Perishable Food." *International Journal of Production Economics* 152: 9–28.
- Govindan, Kannan, Ahmad Jafarian, and Vahid Nourbakhsh. 2019. "Designing a Sustainable Supply Chain Network Integrated with Vehicle Routing: A Comparison of Hybrid Swarm Intelligence Metaheuristics." *Computers and Operations Research* 110: 220–235.
- Gustavsson, J., Cederberg, C., Sonesson, U., Van Otterdijk, R., and Meybeck, A. 2011. "Global food losses and food waste" 1-38. Rome: FAO.
- Harris, Irina, Christine L. Mumford, and Mohamed M. Naim. 2014. "A Hybrid Multi-Objective Approach to Capacitated Facility Location with Flexible Store Allocation for Green

- Logistics Modeling.” *Transportation Research Part E: Logistics and Transportation Review* 66: 1–22.
- Hasani, Aliakbar, Seyed Hessameddin Zegordi, and Ehsan Nikbakhsh. 2012. “Robust Closed-Loop Supply Chain Network Design for Perishable Goods in Agile Manufacturing under Uncertainty.” *International Journal of Production Research* 50 (16): 4649–4669.
- Higgins, A. J., C. J. Miller, A. A. Archer, T. Ton, C. S. Fletcher, and R. R. J. McAllister. 2010. “Challenges of operations research practice in agricultural value chains.” *Journal of the Operational Research Society* 61(6): 964-973.
- Kadambala, Dinesh K, Nachiappan Subramanian, Manoj K Tiwari, Muhammad Abdulrahman, and Chang Liu. 2017. “Closed Loop Supply Chain Networks : Designs for Energy and Time Value Efficiency.” *International Journal of Production Economics* 183: 382–393.
- Kaur, Harpreet, and Surya Prakash Singh. 2017. “Heuristic Modeling for Sustainable Procurement and Logistics in a Supply Chain Using Big Data.” *Computers & Operations Research* 0: 1–21.
- Kelle, Peter, Jinglu Song, Mingzhou Jin, Helmut Schneider, and Christopher Claypool. 2019. “Evaluation of Operational and Environmental Sustainability Tradeoffs in Multimodal Freight Transportation Planning.” *International Journal of Production Economics* 209: 411–420.
- Kumar, Deepak, and Prasanta Kalita. 2017. “Reducing Postharvest Losses during Storage of Grain Crops to Strengthen Food Security in Developing Countries.” *Foods (Basel, Switzerland)* 6 (1).
- Landrigan, Philip J., Richard Fuller, Nereus JR Acosta, Olusoji Adeyi, Robert Arnold, Abdoulaye Bibi Baldé, Roberto Bertollini et al. 2018 "The Lancet Commission on pollution and health." *The Lancet* 391 (10119): 462-512.
- Lemaire, Anais, and Sabine Limbourg. 2019. “How Can Food Loss and Waste Management Achieve Sustainable Development Goals?” *Journal of Cleaner Production* 234: 1221–1234.
- Li, Dong, and Xiaojun Wang. 2017. “Dynamic Supply Chain Decisions Based on Networked Sensor Data: An Application in the Chilled Food Retail Chain.” *International Journal of Production Research* 55 (17). Taylor & Francis: 5127–5141.
- Maghsoudlou, Hamidreza, Mahdi Rashidi Kahag, Seyed Taghi Akhavan Niaki, and Hani Pourvaziri. 2016. “Bi-Objective Optimization of a Three-Echelon Multi-Server Supply-Chain Problem in Congested Systems: Modeling and Solution.” *Computers and Industrial Engineering* 99: 41–62.

- Maiyar, Lohithaksha M., and Jitesh J. Thakkar. 2017. "A Combined Tactical and Operational Deterministic Food Grain Transportation Model: Particle Swarm Based Optimization Approach." *Computers and Industrial Engineering* 110: 30–42.
- Maiyar, Lohithaksha M., Jitesh J. Thakkar, Anjali Awasthi, and Manoj Kumar Tiwari. 2015. "Development of an Effective Cost Minimization Model for Food Grain Shipments." *IFAC-PapersOnLine* 28 (3): 881–886.
- Mahapatra, Maheswar Singha, and Mahanty, Biswajit. 2018. "India's National Food Security Programme: A Strategic Insight." *Sadhana - Academy Proceedings in Engineering Sciences* 43 (12): 1–13.
- Mckinnon, Alan. 2010. "Green Logistics: The Carbon Agenda." *Electronic Scientific Journal of Logistics* 6 (3): 1–9.
- Meneghetti, Antonella, and Luca Monti. 2015. "Greening the Food Supply Chain: An Optimisation Model for Sustainable Design of Refrigerated Automated Warehouses." *International Journal of Production Research* 53 (21): 6567–6587.
- Mogale, D. G., Sri Krishna Kumar, Fausto Pedro García Márquez, and Manoj Kumar Tiwari. 2017. "Bulk Wheat Transportation and Storage Problem of Public Distribution System." *Computers and Industrial Engineering* 104: 80–97.
- Mogale, D. G., Sri Krishna Kumar, and Manoj Kumar Tiwari. 2018. "An MINLP Model to Support the Movement and Storage Decisions of the Indian Food Grain Supply Chain." *Control Engineering Practice* 70: 98–113.
- Mohammed, Ahmed, and Qian Wang. 2017a. "Developing a Meat Supply Chain Network Design Using a Multi-Objective Possibilistic Programming Approach." *British Food Journal* 119 (3): 690–706.
- Mohammed, Ahmed, and Qian Wang. 2017b. "The Fuzzy Multi-Objective Distribution Planner for a Green Meat Supply Chain." *International Journal of Production Economics* 184: 47–58.
- Mohtashami, Ali, Madjid Tavana, Francisco J. Santos-Arteaga, and Ali Fallahian-Najafabadi. 2015. "A Novel Multi-Objective Meta-Heuristic Model for Solving Cross-Docking Scheduling Problems." *Applied Soft Computing Journal* 31: 30–47.
- Moore, Jacqueline, and Richard Chapman. 1999. "Application of Particle Swarm to Multiobjective Optimization." *Department of Computer Science and Software Engineering Department, Auburn University*, 1–4.
- Mousavi, Seyed Mohsen, Javad Sadeghi, Seyed Taghi Akhavan Niaki, and Madjid Tavana. 2016. "A Bi-Objective Inventory Optimization Model under Inflation and Discount Using

- Tuned Pareto-Based Algorithms: NSGA-II, NPGA, and MOPSO." *Applied Soft Computing Journal* 43. Elsevier B.V.: 57–72.
- Musavi, Mir Mohammad, and Ali Bozorgi-Amiri. 2017. "A Multi-Objective Sustainable Hub Location-Scheduling Problem for Perishable Food Supply Chain." *Computers and Industrial Engineering* 113: 766–778.
- Nurjanni, Kartina Puji, Maria S. Carvalho, and Lino Costa. 2017. "Green supply chain design: A mathematical modeling approach based on a multi-objective optimization model." *International Journal of Production Economics* 183: 421-432.
- Oglethorpe, David. 2010. "Optimising Economic, Environmental, and Social Objectives: A Goal-Programming Approach in the Food Sector." *Environment and Planning A* 42 (5): 1239–1254.
- Paksoy, Turan and Özceylan, Eren and Weber, Gerhard-Wilhelm and Barsoum, Nader and Weber, GW and Vasant, Pandian. 2010. "A Multi Objective Model for Optimization of a Green Supply Chain Network." *AIP conference proceedings* 1239: 311--320.
- Parwez, Sazzad. 2014. "Food Supply Chain Management in Indian Agriculture: Issues, Opportunities and Further Research." *African Journal of Business Management* 8 (14): 572–581.
- Pasandideh, Seyed Hamid Reza, Seyed Taghi Akhavan Niaki, and Kobra Asadi. 2015. "Bi-Objective Optimization of a Multi-Product Multi-Period Three-Echelon Supply Chain Problem under Uncertain Environments: NSGA-II and NPGA." *Information Sciences* 292: 57–74.
- Piramuthu, Selwyn, Poorya Farahani, and Martin Grunow. 2013. "RFID-generated traceability for contaminated product recall in perishable food supply networks." *European Journal of Operational Research* 225(2): 253-262.
- Ramanathan, V., S. Sundar, R. Harnish, S. Sharma, J. Seddon, B. Croes, A. Lloyd et al. 2014. "India California air pollution mitigation program: Options to reduce road transport pollution in India." *Published by The Energy and Resources Institute in collaboration with the University of California at San Diego and the California Air Resources Board.*
- Reddy, Reddivari Himadeep, Sri Krishna Kumar, Kiran Jude Fernandes, and Manoj Kumar Tiwari. 2017. "A Multi-Agent System Based Simulation Approach for Planning Procurement Operations and Scheduling with Multiple Cross-Docks." *Computers and Industrial Engineering* 107: 289–300.
- Report of the Comptroller and Auditor General of India. 2013. "Storage Management and Movement of Food Grains in Food Corporation of India." *Union Government Ministry of Consumer Affairs, Food and Public Distribution.*

- Report of the High Level Committee. 2015. "Reorienting the Role and Restructuring of FCI."
- Report of International Energy Agency. 2009. "Green supply chain & logistics climate protection through process optimization: A key performance indicator (KPI) to assess CO2 emissions." *Bayer Business and Technology Services report*.
- Sachan, Amit, B.S. Sahay, and Dinesh Sharma. 2005. "Developing Indian Grain Supply Chain Cost Model: A System Dynamics Approach." *International Journal of Productivity and Performance Management* 54 (3): 187–205.
- Scholz, Katharina, Mattias Eriksson, and Ingrid Strid. 2015. "Carbon Footprint of Supermarket Food Waste." *Resources, Conservation and Recycling* 94: 56–65.
- Seuring, S. 2013. "A Review of Modeling Approaches for Sustainable Supply Chain Management." *Decision Support Systems* 54 (4): 1513–1520.
- Sharon, Magdalene, C V Kavitha Abirami, and K Alagusundaram. 2014. "Grain Storage Management in India." *Journal of Postharvest Technology* 2 (1): 012–014.
- Shrivastava, R. K., Saxena Neeta, and Gautam Geeta. 2013 "Air pollution due to road transportation in India: A review on assessment and reduction strategies." *Journal of environmental research and development* 8 (1): 69.
- Simonson, S. 2009. "Transforming the fresh food supply-chain." *Food Logisti*: 14-15.
- Song, Malin, Shuhong Wang, and Ron Fisher. 2014. "Transportation, Iceberg Costs and the Adjustment of Industrial Structure in China." *Transportation Research Part D: Transport and Environment* 32: 278–286.
- Soto-Silva, Wladimir E., Esteve Nadal-Roig, Marcela C. González-Araya, and Lluís M. Pla-Aragones. 2016. "Operational Research Models Applied to the Fresh Fruit Supply Chain." *European Journal of Operational Research* 251 (2): 345–355.
- Soysal, M., J. M. Bloemhof-Ruwaard, and J. G A J Van Der Vorst. 2014. "Modelling Food Logistics Networks with Emission Considerations: The Case of an International Beef Supply Chain." *International Journal of Production Economics* 152: 57–70.
- Srivastav, Achin, and Sunil Agrawal. 2016. "Multi-Objective Optimization of Hybrid Backorder Inventory Model." *Expert Systems with Applications* 51: 76–84.
- Swaminathan, Jayashankar M., Stephen F. Smith, and Norman M. Sadeh. 1998. "Modeling supply chain dynamics: A multiagent approach." *Decision sciences* 29(3): 607-632.
- Timperley Jocelyn (2019) The Carbon Brief Profile: India <https://www.carbonbrief.org/the-carbon-brief-profile-india>. Accessed on 5 July 2019.

- Teter Jacob, Cazzola Pierpaolo and Petropoulos Apostolos. 2019 “Tracking Clean Energy Progress: Transport”. <https://www.iea.org/tcep/transport/>. Accessed 1 July 2019.
- Trelea, Ioan Cristian. 2003. “The Particle Swarm Optimization Algorithm: Convergence Analysis and Parameter Selection.” *Information Processing Letters* 85 (6): 317–325.
- Validi, Sahar, Arijit Bhattacharya, and P. J. Byrne. 2014a. “A Case Analysis of a Sustainable Food Supply Chain Distribution System - A Multi-Objective Approach.” *International Journal of Production Economics* 152: 71–87.
- Validi, Sahar, Arijit Bhattacharya, and P. J. Byrne. 2014b. “Integrated Low-Carbon Distribution System for the Demand Side of a Product Distribution Supply Chain: A DoE-Guided MOPSO Optimiser-Based Solution Approach.” *International Journal of Production Research* 52 (10): 3074–3096.
- Validi, Sahar, Arijit Bhattacharya, and P. J. Byrne. 2015. “A Solution Method for a Two-Layer Sustainable Supply Chain Distribution Model.” *Computers & Operations Research* 54: 204–217.
- Validi, Sahar, Arijit Bhattacharya, and P. J. Byrne. 2018. “Sustainable Distribution System Design: A Two-Phase DoE-Guided Meta-Heuristic Solution Approach for a Three-Echelon Bi-Objective AHP-Integrated Location-Routing Model.” *Annals of Operations Research*. Springer, 1–32.
- Van Der Vorst, Jack G.A.J., Seth Oscar Tromp, and Durk Jouke Van Der Zee. 2009. “Simulation Modelling for Food Supply Chain Redesign; Integrated Decision Making on Product Quality, Sustainability and Logistics.” *International Journal of Production Research* 47 (23): 6611–6631.
- Verderame, Peter M., and Christodoulos A. Floudas. 2009. “Operational Planning Framework for Multisite Production and Distribution Networks.” *Computers and Chemical Engineering* 33 (5): 1036–1050.
- Wang, Fan, Xiaofan Lai, and Ning Shi. 2011. “A Multi-Objective Optimization for Green Supply Chain Network Design.” *Decision Support Systems* 51 (2): 262–269.
- Wang, Jing, Yue Huili, and Mark Goh. 2018. "Empirical study of sustainable food supply chain management practices in China." *British Food Journal* just-accepted: 00-00. <https://doi.org/10.1108/BFJ-09-2017-0525>.
- Wang, Min, Lindu Zhao, and Michael Herty. 2018. “Modelling Carbon Trading and Refrigerated Logistics Services within a Fresh Food Supply Chain under Carbon Cap-and-Trade Regulation.” *International Journal of Production Research*: 1–19.

Yu, Shiwei, Shuhong Zheng, Shiwei Gao, and Juan Yang. 2017. "A Multi-Objective Decision Model for Investment in Energy Savings and Emission Reductions in Coal Mining." *European Journal of Operational Research* 260 (1): 335–347.

Zhu, Zhanguo, Feng Chu, Alexandre Dolgui, Chengbin Chu, Wei Zhou, and Selwyn Piramuthu. 2018. "Recent Advances and Opportunities in Sustainable Food Supply Chain: A Model-Oriented Review." *International Journal of Production Research*: 1–23.