Designing a food supply chain for enhanced social sustainability in developing countries

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Abstract

The food grain production in India has progressively risen in the past few decades, whereas the storage capacity has remained limited. The policymakers in India are attempting to close this capacity gap while addressing sustainability objectives. However, the quantification and integration of multiple social sustainability factors have remained a challenge. To improve the overall sustainability, the study attempts to develop a mathematical model considering procurement, transportation, inventory, and location-related issues. Several supply chain network factors are integrated and assessed while focussing on the social sustainability dimension. Three cases of India's largest food grain-producing and consuming states are analysed with the help of two Pareto-based algorithms. Multiple relationships between variations in supply, demand, and the capacity of silos with three defined objectives are evaluated. It is observed that, the demand significantly influences the economic and environmental objectives compared with the supply and silo capacity. The capacity of silos has a more significant impact on social objectives than economic and environmental objectives. Results reveal the importance of establishing a sufficient number of modernised silos, which reduces environmental impact and improves social factors such as farmers' economic condition and welfare, balanced economic development, number of jobs created, and public health level. The study supports policymakers in making sustainable decisions within food supply chains.

Keywords: Food supply chains; Social sustainability; Multi-objective modelling; Optimisation; Developing countries.

1. Introduction

The global food demand is likely to increase by 70% in 2050 due to the increasing population (Alexandrato and Bruinsma, 2012). This escalated demand leads to price inflation and augmented business instability and further imposes significant pressure on limited natural resources such as clean water, energy, and land (Govindan, 2018; Sgarbossa and Russo, 2017). Similarly, the demand for food grains (e.g., wheat and rice) in India is continuously increasing, and policymakers in India are trying to expand food production and develop efficient transportation and storage infrastructures to reduce post-harvest losses (Mahapatra and Mahanty, 2018; Anoop et al., 2018; Maiyar and Thakkar, 2020). In India, yearly losses roughly account for 12 to 16 million tonnes of food grains, equivalent to nearly USD 4 billion (Alagusundaram, 2016). Safe storage and reduction of food losses can fulfil 10% of India's food demand. However, when compared with essential capacity, the storage gap has gradually risen over the recent years. Thus, the government and other authorities have shifted their focus to establishing new warehouses and silos to better manage the supply and demand.

The sustainability impact of Food Supply Chains (FSCs) in developing economies needs special attention due to increasing issues associated with food loss and waste primarily driven by climate change and inadequate supply chain activities (Ghadge et al., 2020; Krishnan 2020; Sharma et al., 2020, Singh et al., 2021). The agriculture sector contributes significantly to global warming via Greenhouse Gas (GHG) emissions (Huang and Wang, 2018, Irani et al., 2018). Interestingly, India is the third-largest global GHG emitter after China and the USA (Timperley, 2019). In India, the daily transportation emission of 261 tons of CO2, comes mainly from road transport alone (Shrivastava et al., 2013). In pollution-allied deaths, The Lancet Commission on pollution and health ranked India in the number one position due to 2.51 million pollution-related deaths in 2015 (Landrigan et al., 2018). Furthermore, In India, almost 5 million tons of crops get ruined yearly due to GHG (Ramanathan et al., 2014). Thus, the impact of pollution on the environment and human health is also significant. Limited studies evaluated the environmental effects of FSCs in India, despite being the second-largest producer of food grains and a major exporter of several agricultural products (Sota-Silva et al., 2016). These facets highlight the consideration of environmental factors in the FSC designs and configurations (Mohebalizadehgashti et al., 2020).

As per the High-Level Committee Report (2015), only 6% of all farmers in the country gained benefits from the government's Minimum Support Price (MSP) by selling their food grain to government procurement agencies. Every year, farmers in India face a loss of USD

9.139 billion due to an inability to sell their food grains (Mahapatra, 2018). Due to this major issue, the farmer's economic and welfare growth is not encouraging. This is one of the major reasons along with climate change, high input costs and drought behind farmers' high suicide rate in India (Mariappan and Zhou, 2019; De and Singh, 2020). Every year this suicide rate in India has been growing, and in 2017, a total of 18,098 farmers committed suicide. From 1995 to the present, nearly 0.5 million Indian farmers have ended their lives through 'agriculture-driven' suicides (Mariappan and Zhou, 2019).

Furthermore, hunger and malnutrition are two major challenges currently faced by India. Despite being the world's second-largest producer of food grains, India ranked 94th out of 107 nations in the 2020 global hunger index list (Global Hunger Index, 2020). According to this rating, India's level of hunger is serious. This has made India's path difficult in meeting the United Nation's second sustainable development goal of zero hunger by 2030 (Ritchie et al., 2018). Moreover, the unemployment rate in India has doubled over the last two years and reached 8 percent in Dec 2021 (Biswas, 2022). The above figures indicate that social sustainability issues such as farmers' economic welfare and growth, balanced economic development, job opportunities and malnutrition need special attention while designing food supply chain networks in developing economies (Esteso et al., 2018; Zhu et al., 2018; De and Singh, 2021).

The triple bottom line (TBL) of sustainability encompassing economic, environmental and social dimensions (Martins et al., 2019, Hosseini-Motlagh et al. 2020) is receiving growing attention, especially in the Food Supply Chains (FSCs) to meet the aforementioned challenges. It is imperative to consider such sustainability while designing an agri-food supply chain network (Ghadge et al., 2017, Rohmer et al., 2019, Jonkman et al., 2019, Mogale et al., 2019, Mangla et al. 2018, Mohebalizadehgashti et al. 2020). However, the holistic consideration of all three dimensions of sustainability in agri-food supply chain network design has appeared in a limited number of studies (Esteso et al., 2018, Zhu et al., 2018, Banasik et al., 2019, Mohammed and Wang, 2017a, Govindan, 2018, Martins et al., 2019; Ghadge et al., 2021). It is observed that economic and environmental dimensions are comprehensively (independent as well as combined) discussed in the extant literature, with limited consideration towards the social dimension. Only a few studies (e.g., Varsei and Polyakovskiy, 2017; Allaoui et al., 2018) have managed to integrate all three dimensions; however, the simultaneous integration of TBL varies. Following the dire need for a holistic perspective on sustainability in FSCs, this study aims to design a food supply chain network for enhanced sustainability and make informed decisions for policymakers in developing economies. This study attempts to answer the following research questions: 1. How to integrate three dimensions of sustainability while designing the food grain supply chain? 2. How to quantify the societal factors of social sustainability? 3. What impact do key parameters have on the food grain supply chain network?

While attempting to achieve the defined aim and research questions, this study attempts to provide a sustainable decision support model for FSC policymakers in India. Some of the key contributions this paper is likely to bring are presented below. A mixed-integer non-linear programming (MINLP) model is developed to design a sustainable food grain supply chain network, simultaneously optimising total network costs, environmental impact (emissions) and defined social benefits. To the best of our knowledge, this is the first attempt to concurrently embed economic and environmental factors along with key social factors, namely the number of jobs generated, balanced economic development, farmers' economic welfare and growth rate, and public health in a multi-objective optimisation model for agri-food supply chain networks. Additionally, the various realistic and practical aspects of the problem encompassing multiple periods, echelons, transportation modes, sourcing and distribution are simultaneously considered while developing the model. The varied capacitated vehicles and their restricted accessibility in producing and consuming states are additional proposed model features. A multi-objective particle swarm optimisation algorithm with gbest, lbest and nbest social structure (MOGLNPSO) is transformed to solve three objective optimisation models. Comparative analysis is conducted with the Multi-Objective Particle Swarm Optimization (MOPSO). Policymakers can conduct the viability analysis of the prospective locations of silos using the proposed model to dodge the forfeiture of the initial investment. The management authorities could quickly transport the food stock from the producing region to the consuming region, reducing post-harvest losses.

The rest of the paper proceeds as follows: Section 2 is dedicated to the literature review. Section 3 provides an overview of the underlying problem and context of a case study. Section 4 presents the model development, including notations and formulation. Section 5 deals with the multi-objective meta-heuristic algorithms employed in the paper. The results and sensitivity analysis are discussed in section 6. Finally, the concluding remarks and future scope are provided in section 7.

2. Literature Review

The relevant literature focuses on the design of FSC networks and sustainability characteristics in FSCs.

2.1 Food supply chain network design

Various academic reviews, including Akkerman et al. (2010), Soto-Silva et al. (2016), Shukla and Jharkharia (2013), Ahumada and Villalobos (2009), Esteso et al. (2018) and Zhu et al. (2018), discuss multiple decision support models for the FSC network design and identify the scarcities of model(s) with the integration of specific factors like the number of jobs created, balanced economic development, economic welfare of farmers, and public health levels. The importance of multi-objective mathematical models to tackle FSC problems in emerging economies was recently highlighted by Esteso et al. (2018) and Zhu et al. (2018). The various issues starting from the farmer through to the customer, need of sustainability, lack of consideration of all actors, amalgamation of the intrinsic features and complex network of FSCs are deliberated in these studies. These studies also argued the necessity of considering multi-time-period scenarios and incorporation of procurement, transport, inventory decisions, and sustainability. Additionally, for further reference, interested readers can refer to the review articles by Utomo et al. (2018), Bordin et al. (2016) and Beske et al. (2014) on sustainable FSCs.

The uncertain and complex nature of the food systems make cost and benefit assessment more challenging (Zhao et al., 2021). The majority of facility location or Supply Chain Network Design (SCND) problems in FSCs emphasises the cost objective (Aras and Bilge, 2018, Etemadnia et al., 2015; Nourbakhsh et al., 2016; Orjuela-Castro et al., 2017; Rancourt et al. 2015; Gholami-Zanjani et al., 2021). The inclusion of multi-period and holistic integration of economic, environmental and societal features are needed for a comprehensive assessment of FSC design (Mohammed and Wang 2017a).

2.2 Sustainability characteristics in food supply chains

According to Khan et al. (2021), a maximum number of papers published in the domain of sustainable supply chain management covers economic and environmental dimensions, and only a few papers consider all three sustainability dimensions. Few scholars have evaluated the environmental impact of FSCs through bi-objective modelling of different problems such as a beef logistics network (Soysal et al., 2014), closed-loop mushroom supply chain (Banasik et al., 2017), location routing (Validi et al., 2020; Govindan et al., 2014), fresh food delivery (Bortolini et al., 2018), beef and dairy network design (Rohmer et al., 2019), food grain supply chain (Mogale et al., 2019) and supply chain network design (Validi et al., 2014, 2020). All the realistic characteristics of FSCs such as numerous stages, finite planning horizon, transport modes, procurement, distribution, and capacitated warehouses are limited or missing in the above studies. Also, other crucial factors like carbon footprint, mixed capacitated vehicles and their restricted accessibility have appeared in very limited studies on sustainable FSCs.

2.3 Research gaps and motivations

A comprehensive review of key papers describing the main characteristics, components of objective functions, decisions considered in the model and solution methods is provided in Table 1. It is observed that most scholars have modelled the problem as Mixed-Integer Linear Programming (MILP) and considered multi-echelon scenarios. Facility location and transportation are considered in several models. It is also noticed that most researchers have not integrated the emissions from inventory-holding in their models. Allaoui et al. (2018) and Varsei and Polyakovskiy (2017) have attempted to model the supply chain network design problem in the form of three objectives. However, the economic and environmental impact of inventory has been overlooked in these studies. Furthermore, balanced economic development, economic welfare, growth of farming, and public health have not been considered in the social objective. Consideration of multiple factors associated with the social dimension along with a lack of holistic integration of TBL in FSCs design acts as a motivation for the development of a comprehensive FSC model for enhanced social sustainability. This will further support making informed decisions for policymakers in developing economies. Furthermore, the majority of studies in the literature employed the MOPSO and NSGA-II algorithms but ignored the application of the recently developed MOGLNPSO algorithm to solve the complex FSCs problems. This is evident from the last column of Table 1.

Table 1 Summary of the main features and objective functions of existing relevant literature

Modelling features: ME: Multiple echelons, MP: Multiple periods, MM/I: Multiple modes/intermodal
Modelling: LP: Linear programming; MIP= Mixed integer programming; MILP= Mixed integer linear programming; MINLP = Mixed integer non-linear programming.
Economic objective: FLC= Facility location cost; TRC= Transportation cost; INC= Inventory cost.
Environmental objective: CO_2 emission produced due to FE= Facility establishment; TR= Transportation; INH= Inventory holding,
Social objective: NJC=Number of job opportunities created; BED= Balanced Economic development; FEWG= Economic welfare and growth of farmers; PH= Public Health.
Decisions: Loc: Location; All: Allocation; CL: Capacity level; FS: Fleet Sizing; TR: Transportation; IN: Inventory

	Modelling features				Objective functions																Solution Methods
					Economic objective			Environmental objective			Social objective				Decision topics						
Reference articles	ME	MP	MM/E	Modelling	FLC	TRC	INC	FE	TR	INH	NJC	BED	FEWG	PH	Loc	All	CL	FS	TR	IN	
Allaoui et al. (2018)	●	●	●	MILP	●	●		●	●		●				●				●		Epsilon constraint
Banasik et al. (2017)	●	●		MILP	●	●			●						●	●			●		Epsilon constraint
Govindan et al. (2014)	●	●		MIP	●	●		●	●						●				●		MOPSO and NSGA-II
Mohebalizadehgashti et al. (2020)	●	●		MILP	●	●			●						●	●			●		Epsilon constraint
Mohammed and Wang (2017b)	●			MILP		●		●	●						●				●		LP metrics, Epsilon constraint and goal programming
Asian et al. (2019)	●			NLP		●	●									●			●	●	Heuristic
Mogale et al. (2019)	●	●	●	MINLP	●	●	●	●	●	●					●			●	●	●	MOPSO and NSGA-II
Validi et al. (2020)	●	●		MILP	●	●			●						●	●			●		MOGA-II
Soysal et al. (2014)	●	●	●	MILP		●	●		●									●	●	●	Epsilon constraint
Validi et al. (2014)	●			MIP	●	●			●						●	●		●	●		NSGA-II and MOGA-II
Jonkman et al. (2019)	●	●		MILP	●	●	●		●						●				●	●	Epsilon constraint
Varsei and Polyakovskiy (2017)	●		●	MIP	●	●	●		●		●	●			●	●	●		●	●	Epsilon constraint
Rohmer et al. (2019)	●		●	LP		●			●										●		Epsilon constraint
Bortolini et al. (2018)	●	●	●	MILP	●	●	●	●	●						●				●	●	Normalised Normal Constraint Method
Maiyar and Thakkar (2020)	●	●	●	MINLP	●	●			●						●	●			●		PSODE
This research	●	●	●	**MINLP**	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	●	**MOGLNPSO and MOPSO**

3. Problem overview and case study

Problem overview

The food supply chain network considered in this paper comprises procurement centres, base, field, regional silos and fair price shops (see Figure 1). The problem under study is a multi-echelon and multi-period food SCND problem considering three pillars of sustainability. To better manage supply and demand, the policymakers in India need to establish the number of warehouses and silos to bridge the storage capacity gap, increase food procurement from farmers and provide the food grains at subsidised rates to economically poor people of the society by simultaneously optimising sustainability objectives. The key decisions to be addressed through this study are to determine the locations and capacity levels of base, field and regional silos (strategic), allocations between the various echelons, number of mixed capacitated vehicles utilised and food grain flow between the various supply chain stages and inventory level. The food loss percentage in the bulk food supply chain is significantly less; thus, transit and storage loss is not considered in this study.

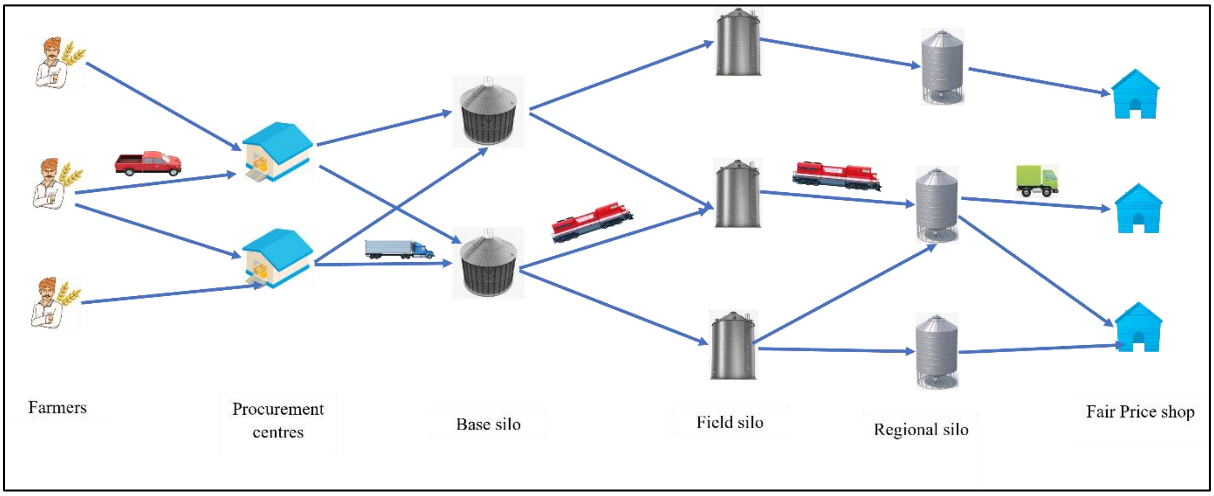


Figure 1: Schematic representation of food grain supply chain network in India.

Figure 1 Alt Text: Food grain supply chain network depicting farmers, procurement centres, base silos, field silos, regional silos and fair price shops along with different vehicle and rail movements

Case study

This study is related to the food SCND based in India. India is a large consumer of agri-food and the second leading food grain (wheat and rice) producer after China (Sharma et al., 2013, Mogale et al., 2017, Mangla et al., 2018). The Public Distribution System (PDS) is a national food security system in India, which supplies food grains at lower prices to economically weak sections of the society (High-Level Committee Report, 2015). This is the world's largest food delivery system of its kind (Kishore and Chakrabarti, 2015). Procurement, storage, movement, and distribution are various operations of the food grain supply chain, which are handled by the Food Corporation of India (FCI). Initially, farmers supply the food grains to procurement centres, which are managed by the FCI and state agencies from the producing states at a MSP rate. The procured food grain is then dispatched to the base silos and central warehouses. In the next stage, food grain is allotted to the numerous consuming states based on their demand and offtakes in the last period (Mogale et al., 2018). Finally, the consuming states distribute the food grain to end consumers through Fair Price Shops (FPS). Normally, road freight is used for intrastate transportation, whereas rail freight is used for interstate transportation (Mogale et al., 2017).

The proposed model is applied to the real-life case study pertaining to the leading wheat surplus state (Punjab) and deficit state (Maharashtra) in India. These two states are located in geographically dispersed regions. Punjab comes under the north zone of India and Maharashtra is one of the Indian states from the central zone. During the food grain yield season of 2017-18, state government agencies, along with the FCI, procured 11.833 million tons of rice through several purchase centres established across the Punjab state (FCI, 2018). The procurement in Maharashtra in the same period was only 0.179 million tons, which was insufficient to fulfil the demand for rice. Due to this mismatch between procurement and demand, the decision makers transported the surplus food grain from Punjab to Maharashtra through rail. Three data sets with varying echelons and periods from different regions of these two states were gleaned through several field visits, reports (CAG, 2013) and online sources (https://www.indiastat.com/).

4. Model formulation

The economic factors like facility location, transportation, and inventory costs were mainly considered by Jonkman et al. (2019), Mogale et al. (2019) and Bortolini et al. (2018). Transportation emission is the key element in environmental objectives in previous studies. Few scholars such as Govindan et al. (2014) and Mohammed and Wang (2017b) embedded the emission produced by facility location into the mathematical model. Furthermore, Mogale et al. (2019) introduced the emission produced by inventory holding. Regarding the social objective function, Allaoui et al. (2018) focused on a number of job opportunities created; Whereas, Varsei and Polyakovskiy (2017) looked at the balanced economic development. Farmer's economic and welfare growth and public health factors were not investigated by the previous authors. Major studies explored the facility location-allocation and transportation decisions. The capacity level, fleet sizing and inventory decisions were not appeared along with other decisions. Multiple generic constraints such as supply, demand and storage capacity constraints were taken into account by Maiyar and Thakkar (2020), Mogale et al. (2019), Banasik et al. (2017) and Bortolini et al. (2018) while developing their model(s). However, the silo's capacity level selection and vehicle capacity constraint are not observed in the above papers. Thus, this study considers all these factors simultaneously while developing a proposed multi-objective mathematical model.

The sustainable food grain SCND problem is formulated as a multi-objective mixed-integer non-linear programming model. The assumptions considered while formulating the model and objective functions are described below. The detailed description of the model notations including sets, indices, parameters and decision variables used in the formulation is provided in Appendix A due to brevity.

Assumptions:

1. Candidate sites of locating silos are known and fixed.
2. The restricted mixed capacitated vehicles in each period are taken into account while transferring the food grain.
3. Full Truck Load (FTL) transport scenario is considered.
4. The availability of food grain and demand is deterministic.

Objective functions

Economic objective (Minimisation of total supply chain cost)

***Min Obj*₁:** Silo construction fixed cost + Transportation cost + Inventory cost (1)

The economic objective function of the model, as shown in Eq. (1), comprises silo construction fixed costs, transportation costs and inventory holding costs.

$$\text{Silo construction fixed cost} = \sum_{j,n} fc_{jn} X_{jn} + \sum_{k,p} fc_{kp} Y_{kp} + \sum_{l,q} fc_{lq} Z_{lq} \quad (1.1)$$

Eq. (1.1) depicts the fixed costs of base, field and regional silo establishments.

Transportation cost =

$$\sum_{i,j,t} a\ d_{ij} E_{ij}^{t} + \sum_{j,k,t} b\ d_{jk} F_{jk}^{t} + \sum_{k,l,t} a\ d_{kl} G_{kl}^{t} + \sum_{l,m,t} a\ d_{lm} H_{lm}^{t} \quad (1.2)$$

Eq. (1.2) indicates the transportation costs from procurement centre to base silo, base to field silo, field to regional silo and regional silo to fair price shops.

Inventory cost = $\sum_{j,t} e_j inj_j^t + \sum_{k,t} e_k ink_k^t + \sum_{l,t} e_l\ inl_l^t$ (1.3)

Eq. (1.3) illustrates the inventory holding cost at base, field and regional silos.

Environmental objective (Minimisation of CO_2 emission)

Min Obj₂ = Emission generated due to silo construction + Transportation emission

+ Emission produced due to inventory holding (2)

The environmental objective function of the model as shown in Eq. (2), represents the minimisation of the sum of total CO_2 emissions. It includes carbon emissions produced due to silo construction, transportation and inventory storage.

The emissions generated due to silo establishment = $\sum_{j,n} \varepsilon o_{jn} X_{jn} + \sum_{k,p} \varepsilon o_{kp} Y_{kp} + \sum_{l,q} \varepsilon o_{lq} Z_{lq}$ (2.1)

Eq. (2.1) portrays the CO_2 emissions generated due to the base, field and regional silos establishment.

The emissions generated due to transportation =

$$\sum_{i,j,r,t} \varepsilon t_{ij}^{r} d_{ij} \rho_{ij}^{rt} + \sum_{j,k,s,t} \varepsilon t_{jk}^{s} d_{jk} \Delta_{jk}^{st} + \sum_{k,l,u,t} \varepsilon t_{kl}^{u} d_{kl} \beta_{kl}^{ut} + \sum_{l,m,v,t} \varepsilon t_{lm}^{v} d_{lm} \mu_{lm}^{vt} \quad (2.2)$$

Eq. (2.2) illustrates the emissions generated due to transportation of food grain stock from procurement centre to base silo, base to field silo, field to regional silo and regional silo to fair price shops.

The emissions produced due to inventory holding = $\sum_{j,t} \varepsilon i_j inj_j^t + \sum_{k,t} \varepsilon i_k ink_k^t + \sum_{l,t} \varepsilon i_l inl_l^t$ (2.3)

The CO_2 emissions generated due to holding of inventories at base, field and regional silo are represented by Eq. (2.3).

Social objective (Maximisation of social benefits)

Max Obj₃ = [(weight of jobs created* created job opportunities) + (weight of balanced economic development* balanced economic development) + (weight of economic welfare and growth rate of farmers* economic welfare and growth rate of farmers) + (weight of public health*public health)] (3)

The social objective as depicted in Eq. (3) tries to maximise the number of job opportunities created, balanced economic development, economic welfare and growth rate of farmers and public health level.

Created job opportunities =

$$\gamma_{jc}\left(\begin{array}{l}\sum_{j,n} ue_j\, jc_{jn} X_{jn} + \sum_{k,p} ue_k\, jc_{kp} Y_{kp} + \sum_{l,q} ue_l\, jc_{lq} Z_{lq} + \sum_{j,t} ue_j \left(inj_j^t / mhc\right) + \\ \sum_{k,t} ue_k \left(ink_k^t / mhc\right) + \sum_{l,t} ue_l \left(inl_l^t / mhc\right)\end{array}\right) \quad (3.1)$$

Eq. (3.1) depicts the number of fixed and variable job opportunities created. The first three terms show the fixed-job opportunities created through the construction of base, field and regional silos. Variable jobs are considered based on the inventory available in different silos. Workers are required to manage the inventory stored in different silos. Thus, the last three terms depict the variable jobs created based on the available inventory in the silos or warehouses.

Balanced economic development =

$$\gamma_{be}\left(\sum_{j,n} X_{jn}\pi_{jn}\left(1-\phi_j\right) + \sum_{k,p} Y_{kp}\pi_{kp}\left(1-\phi_k\right) + \sum_{l,q} Z_{lq}\pi_{lq}\left(1-\phi_l\right)\right) \quad (3.2)$$

The balanced economic development level of a particular region where base, field and regional silos are to be located is represented by Eq. (3.2).

Economic welfare and growth of farmers = $\gamma_{ewg}\left(\sum_{i,j,t} E_{ij}^t\left(1-\xi_i\right)\right)$ (3.3)

The economic welfare and growth level of farmers assigned to procurement centre i is as shown in Eq. (3.3). If the food grain stock is quickly transferred from the procurement centre to the base silo, then more stock would be purchased from farmers in the procurement centre. This helps farmers to obtain the benefits of MSP and improve their economic welfare and growth rate.

$$\text{Health level of beneficiaries}=\gamma_{ph}\left(\sum_{l,m,t} H_{lm}^{t}\left(1-\psi_{m}\right)\right) \tag{3.4}$$

The health level of people who are buying the food grain from fair price shops is portrayed by Eq. (3.4) which can be maximised by supplying the desired amount of food grain or meeting the customer demand.

Subject to constraint

$$\sum_{j} E_{ij}^{t} \leq A_{i}^{t} \qquad \forall i, \forall t \tag{4}$$

$$E_{ij}^{t} \leq \Phi W_{ij}^{t} \qquad \forall i, \forall j, \forall t \tag{5}$$

$$W_{ij}^{t} \leq \sum_{n} X_{jn} \qquad \forall i, \forall j, \forall t \tag{6}$$

Constraint (4) depicts the supply constraint of the procurement centre. Constraint (5) confirms that food grain should be moved to the assigned base silo only. Procurement centre should be allocated to the established base silo (Constraint 6).

$$\sum_{k} F_{jk}^{t} \leq inj_{j}^{t} \qquad \forall j, \forall t \tag{7}$$

$$F_{jk}^{t} \leq \Phi W_{jk}^{t} \qquad \forall j, \forall k, \forall t \tag{8}$$

$$W_{jk}^{t} \leq \sum_{n} \sum_{p} X_{jn} Y_{kp} \qquad \forall j, \forall k, \forall t \tag{9}$$

Constraint (7) indicates that the total shipment quantities from base silo should not exceed the available inventory at base silo. Constraint (8) denotes that food grain stock from base to field silo should be transferred to the allocated field silo. The shipment between base and field silos occurs if both silos are established (Constraint 9).

$$\sum_{l} G_{kl}^{t} \leq ink_{k}^{t} \qquad \forall k, \forall t \tag{10}$$

$$G_{kl}^{t} \leq \Phi W_{kl}^{t} \qquad \forall k, \forall l, \forall t \tag{11}$$

$$W_{kl}^{t} \leq \sum_{p} \sum_{q} Y_{kp} Z_{lq} \qquad \forall k, \forall l, \forall t \tag{12}$$

Constraint (10) depicts the supply constraint of field silo. Constraint (11) and (12) guarantees that food grain must be transported to the allocated regional silos from field silo, and field silo can only assign if field and regional silos are constructed, respectively.

$$\sum_{m} H_{lm}^{t} \leq inl_{l}^{t} \qquad \forall l, \forall t \tag{13}$$

$$H_{lm}^{t} \leq \Phi W_{lm}^{t} \qquad \forall l, \forall m, \forall t \tag{14}$$

$$W_{lm}^{t} \leq \sum_{q} Z_{lq} \qquad \forall l, \forall m, \forall t \tag{15}$$

Similarly, the supply limit of regional silo in each time period is represented by Constraint (13) and Constraint (14) is the big *M* constraint. The regional silo can be assigned to the fair price shops only when the regional silo is established, and this is indicated by Constraint (15).

$$\sum_{l} H_{lm}^{t} = D_{m}^{t} \qquad \forall m, \forall t \tag{16}$$

Constraint (16) makes sure that the demand of each fair price shop must be fulfilled in a given time period.

$$inj_{j}^{t-1} + \sum_{i} E_{ij}^{t} - \sum_{k} F_{jk}^{t} = inj_{j}^{t} \qquad \forall j, \forall t \tag{17}$$

$$ink_{k}^{t-1} + \sum_{j} F_{jk}^{t} - \sum_{l} G_{kl}^{t} = ink_{k}^{t} \qquad \forall k, \forall t \tag{18}$$

$$inl_{l}^{t-1} + \sum_{k} G_{kl}^{t} - \sum_{m} H_{lm}^{t} = inl_{l}^{t} \qquad \forall l, \forall t \tag{19}$$

Constraints (17) – (19) illustrate the flow balance constraint for base, field and regional silos respectively.

$$inj_{j}^{t} \leq \sum_{n} X_{jn} scap_{jn} \qquad \forall j, \forall t \tag{20}$$

$$ink_{k}^{t} \leq \sum_{p} Y_{kp} scap_{kp} \qquad \forall k, \forall t \tag{21}$$

$$inl_{l}^{t} \leq \sum_{q} Z_{lq} scap_{lq} \qquad \forall l, \forall t \tag{22}$$

Constraint set (20) – (22) enforces the storage capacity constraint for base, field, and regional silos, respectively.

$$\sum_{n} X_{jn} \leq 1 \qquad \forall j \tag{23}$$

$$\sum_{p} Y_{kp} \leq 1 \qquad \forall k \tag{24}$$

$$\sum_{q} Z_{lq} \leq 1 \qquad \forall l \tag{25}$$

Constraints (23) and (25) describe that, at most, one type of capacity level must be selected for each base, field and regional silo establishment, respectively.

$$E_{ij}^{t} \leq \sum_{r} \rho_{ij}^{rt} \alpha_{r} \qquad \forall i, \forall j, \forall t \tag{26}$$

$$F_{jk}^{t} \leq \sum_{s} \Delta_{jk}^{st} \alpha_{s} \qquad \forall j, \forall k, \forall t \tag{27}$$

$$G_{kl}^{t} \leq \sum_{u} \beta_{kl}^{ut} \alpha_{u} \qquad \forall k, \forall l, \forall t \tag{28}$$

$$H_{lm}^{t} \leq \sum_{v} \mu_{lm}^{vt} \alpha_{v} \qquad \forall l, \forall m, \forall t \tag{29}$$

The vehicle capacity constraints between procurement centre to base silo, base to field silo, field to regional silos, and from there to fair price shops are represented by Constraint set (26) – (29) respectively.

$$\sum_{j} \rho_{ij}^{rt} \leq \omega_{ri}^{t} \qquad \forall i, \forall r, \forall t \tag{30}$$

$$\sum_{k} \Delta_{jk}^{st} \leq \omega_{sj}^{t} \qquad \forall j, \forall s, \forall t \tag{31}$$

$$\sum_{l} \beta_{kl}^{ut} \leq \omega_{kl}^{t} \qquad \forall k, \forall u, \forall t \tag{32}$$

$$\sum_{m} \mu_{lm}^{vt} \leq \omega_{lm}^{t} \qquad \forall l, \forall v, \forall t \tag{33}$$

Constraint (30) restricts the number of heterogeneous capacitated vehicles utilised between procurement centres to base silo to maximum vehicles existing at the procurement centre in a given period. Similarly, the limit on the number of vehicles used between base to field silo, field to regional silos and regional silo to fair price shops are illustrated by Constraints (31) – (33).

$$X_{jn}, Y_{kp}, Z_{lq}, W_{ij}^{t}, W_{jk}^{t}, W_{kl}^{t}, W_{lm}^{t} \in \{0,1\} \qquad \forall i, \forall j, \forall k, \forall l, \forall m, \forall n, \forall p, \forall q, \forall t \tag{34}$$

Constraint (34) is the binary variable constraint.

$$E_{ij}^{t}, F_{jk}^{t}, G_{kl}^{t}, H_{lm}^{t}, inj_{j}^{t}, ink_{k}^{t}, inl_{l}^{t} \geq 0 \qquad \forall i, \forall j, \forall k, \forall l, \forall m, \forall t \tag{35}$$

Constraint (35) is the non-negativity constraints.

$$\rho_{ij}^{rt}, \Delta_{jk}^{st}, \beta_{kl}^{ut}, \mu_{lm}^{vt} \in \mathbb{Z}^{+} \qquad \forall i, \forall j, \forall k, \forall l, \forall m, \forall r, \forall s, \forall u, \forall v, \forall t \tag{36}$$

Constraint (36) is the integrity constraint.

5. Solution procedure

The developed model considers several decision variables, parameters, objectives and real-life constraints in comparison with a normal multi-objective SCND problem. Thus, effective and efficient algorithms are needed to solve the complex real-life sustainable food supply chain problems in a reasonable computational time (Steever et al., 2019; Wari and Zhu, 2016; Esteso et al., 2018; Zhu et al., 2018). Among several metaheuristic algorithms, PSO has become popular due to its ease of implementation, effective memory and capability of endowing good convergence (Chakraborty et al., 2011; Sethanan and Neungmatcha, 2016; De et al., 2017). Thus, the multi-objective version of the PSO algorithm is utilised to solve different practical complex problems like distribution network problem (Validi et al., 2014), location-routing problem (Govindan et al., 2014, 2019) and vehicle routing (De et al., 2017). Similarly, Sethanan and Neungmatcha, (2016) have developed a gbest, lbest and nbest particle swarm optimisation (GLNPSO) algorithm with multiple social structures to improve the exploration capability of MOPSO. We proposed to solve the problem with the multi-objective GLNPSO algorithm, as it is well adapted to the situation and performs better on route planning problems compared with MOPSO (Sethanan and Neungmatcha, 2016). This is the first case where the GLNPSO algorithm is applied to address the sustainable food supply chain (SFSC) network design problem. Due to the stochastic search of the GLNPSO algorithm, MOPSO, which is one of the best, most popular and robust multi-objective algorithms is used to compare solutions (Govindan et al., 2014).

5.1 Multi-objective Global, Local and Neighboured Particle Swarm Optimization (MOGLNPSO) algorithm

The PSO algorithm, first proposed by Eberhart and Kennedy (1995), was stimulated from the social behaviour of bird flocking and fish schooling to search the global optima. This is a stochastic and population-based optimisation technique, which uses the movement of individuals for searching (Boonmee and Sethanan 2016). The solution details of the problem are encoded in the particle, which has two crucial features including velocity and position. The objective function value is used to determine the position of each particle in the search space, while velocity is based on distance from one position to another (Sethanan and Neungmatcha, 2016). The velocity and position of each particle are generated through random initialisation of swarms or groups of particles. Particles use cognitive and social behaviour information while finding a better position with a certain velocity in the solution space. The best position of each particle (pbest) and overall swarm (gbest) are updated after attaining each new position. The algorithm stops once it reaches the termination criteria and provides the near-optimal solution of best particle. In the conventional PSO algorithm, each particle uses the global best position to communicate with other particles. This results in the quick gathering of the swarm, which may take the solution to local entrapment (Sethanan and Neungmatcha, 2016, De et al., 2019). Therefore, multiple scholars have developed different variants of a conventional PSO and hybridised it with other local search algorithms to improve performance (Govindan et al., 2014, 2019; Pratchayaborirak and Kachitvichyanukul, 2007; Wang and Yeh, 2014; Lin et al., 2013, Mogale et al., 2018; Wang, 2020). The PSO, combined with gbest, lbest and nbest social structure (GLNPSO), is an effective and fascinating technique among the large variants. It can simultaneously explore various sections of the solution space (Pongchairerks and Kachitvichyanukul, 2005, 2006). Following the features of this GLNPSO algorithm, the single objective GLNPSO algorithm is transformed into a multi-objective GLNPSO, to solve the three objective optimisation models discussed in this paper.

In the GLNPSO algorithm, each individual communicates with several certain sub-clusters of the swarm. The particle velocity is updated using personal best position (pbest), global best position (gbest), local best position (lbest) and near neighbour best position (nbest) for performance improvement. The local best position is a best position identified by any particle among multiple neighbouring particles. The near neighbour best position is evaluated following the fitness-distance ratio (FDR) suggested by Veeramachaneni et al. (2003). It delineates the collaboration among the particles to obtain a better solution. In addition to the current velocity, pbest and gbest, GLNPSO makes use of nbest and lbest while updating the particle velocity. Eq. (5.1) and (5.2) are employed to update the velocity and position of the particle, respectively.

$$\omega_i^{t+1} = w\omega_i^t + c_p u\left(pbest_i^t - \sigma_i^t\right) + c_g u\left(gbest - \sigma_i^t\right) + c_l u\left(lbest_i^t - \sigma_i^t\right) + c_n u\left(nbest - \sigma_i^t\right) \quad (5.1)$$

$$\sigma_i^{t+1} = \sigma_i^t + \omega_i^{t+1} \quad (5.2)$$

Here, ω_i^t and σ_i^t illustrates the velocity and position of *i*th particle in *t*th iteration. Next, the $pbest_i^t$, $gbest_i^t$ $lbest_i^t$ and $nbest_i^t$ represents the personal, global, local and neighbour best position of *i*th particle in *t*th iteration respectively. The inertia, cognitive and social coefficients are depicted by *w*, c_p and c_g respectively. The c_l and c_n denote the acceleration constant of local and near neighbour best positions. The uniformly distributed random number is shown by symbol *u*. Like other metaheuristics, the proposed MO-GLNPSO algorithm is implemented in different stages as represented in pseudocode 1. In the first step, model and algorithmic parameters are provided as input to the algorithm. Next, populations of particles are randomly initialised, and boundary constraint handling methods are employed to ensure the feasibility of particles. In the third step, the fitness functions are determined, and non-dominated solutions are evaluated. Following the GLNPSO scheme, the current particle is updated in the fourth step. Next, the set of Pareto optimal solutions is updated following the crowding distance. The algorithm provides the output after satisfying the termination criteria.

Algorithm 1: The pseudo-code of MOGLNPSO algorithm

```
Function: MOGLNPSO
Start
   Input data and parameters
   Initialization of swarm
  Generatation of I initial particles with random position based on encoding scheme
  Decoding of the particle to the required solution
  Evaluate the fitness function of each particle
  Initialize the pareto optimal archive set
 Set iter = 0
  while iter < Max_iter
     for each particle do
        Update the pbest, if fitness (P_i) < fitness (pbest_i), then pbest_i = P_i Endif
        Update the gbest, if fitness (pbest_i) < fitness (gbest_i), then gbest_i = pbest_i Endif
        Update the lbest, select the pbest_i from its M-neighbours based on least fiteness value
        Update the nbest, for v = .....I and h = 1.....H (H is the size of dimension),
            determine the p_oh with maximum FDR and then set p_oh ← p_ih^nbest
        Update the velocity and position of the each particle using eq. (1) and (2)
        if the re-initilisation criterion satisfy then reinitlise the particle Endif
     end for
     Update the archive set
     iter = iter + 1
  end while
  report solutions in archive
End
```

Particle representation and initialisation

As already stated, a particle represents a solution to the problem. Each particle is comprised of four components: (1) location-allocation (2) capacity level allocation (3) amount of flow and inventory level (4) number of vehicles utilised. The first two components are binary coded, while the remaining two are real coded. The location-allocation component shows whether a particular location is selected for establishing any silo. It consists of various sub-components, each representing an allocation process for each stage of a given set of locations of procurement centres and fair price shops.

The capacity-level allocation component has been defined to check whether the establishment at some chosen location is made of a particular standard of capacity. It consists of three subcomponents, one each representing base, field and regional silo locations. The third component has two subcomponents: (1) The amount of food grain transferred from one stage to immediately below in a particular time period; (2) the amount of food grain present at any stage at the end of any time period. Thus, it takes into consideration the amount available from the previous period, the amount received for the current period and the amount transferred to the next stage in the current period. The fourth component has been defined to calculate and analyse the effect of selecting some specific number of heterogeneous capacitated vehicles at any stage. Non-dominated sorting is a procedure to prepare various sets of solutions, where no solution in that particular set dominates any other solution (Deb et al. 2002). Crowding distance tells about the density of a particular individual solution's neighbourhood region. In this study, the mean distance of two neighbourhood solutions on each side along each objective function is determined. Crowding distance is allocated front-wise. These two operators are identical to the NSGA-II operators; for more insights, interested readers can refer to the Deb et al. (2002) work.

6. Case results and discussion

The configuration of small, medium and large size case types with procurement centres, silos, fair price shops and their time periods are considered as shown in Figure 2. Following the set of available data, the small case classification typically comprised of [S(8-3-4-5-12-2)] eight procurement centres, three potential locations of base silos, four potential locations of field silos, five potential locations of regional silos, 12 fair price shops and two time periods. It also designates the number of variables and constraints present in each case type. Parameter tuning helps to find better solutions with minimum computational time, which can increase the effectiveness and efficiency of algorithms (Mogale et al., 2017). Therefore, numerous preliminary computational experiments are conducted on different cases to determine suitable parameters. The calibrated values for MOGLNPSO parameters are Population size: 100, Maximum iteration = 500, Inertia weight: 0.9, Number of adjacent neighbours = 5, pbest, gbest, lbest and nbest = 1. Both algorithms are coded in Matlab (R2018a) software and run on the workstation with Intel Core i5, 2.90 GHz processor and 8 GB RAM. All the cases are solved using the two proposed algorithms along with calibrated parameters to generate Pareto solutions. Table 2 presents computational results in the form of 'minimum', 'intermediate' and 'maximum' values of each objective function. The 'minimum' and 'maximum' depicts the lowest and highest value of a specific objective in the Pareto front. All three objectives are dealt with similarly and specify equal importance while determining the Pareto optimal solution (intermediate).

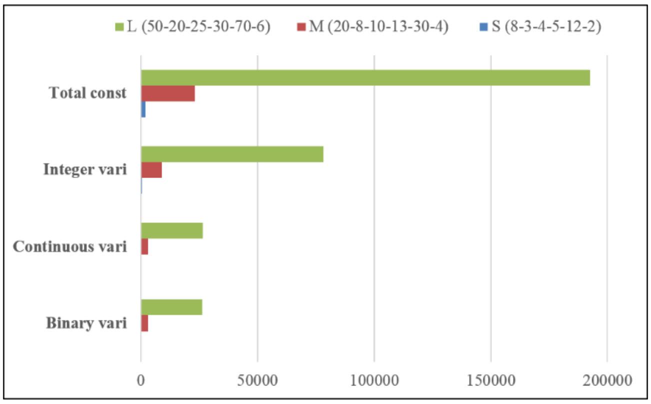


Figure 2 Three problem cases and associated decision variables and constraints

Figure 2 Alt Text: Bar chart illustrating total constraints and variables for small, medium, and large cases

Table 2 Summary of the computational results obtained by proposed algorithms

	Results obtained through MOGLNPSO algorithm									
Case no	*(min)Obj1*			*(min)Obj2*			*(max)Obj3*			CPU time (s)
	min	inter	max	min	inter	max	min	inter	max	
1	4.73×10^6	4.82×10^6	9.96×10^6	7.28×10^7	1.84×10^8	2.09×10^8	3.80×10^5	3.91×10^5	7.61×10^5	320.08
2	1.02×10^7	1.18×10^7	2.71×10^7	8.48×10^7	2.97×10^8	1.89×10^9	8.91×10^6	8.96×10^6	1.21×10^7	1632.78
3	3.16×10^7	3.23×10^7	3.27×10^7	1.59×10^{10}	1.73×10^{10}	1.86×10^{10}	1.28×10^8	1.45×10^8	1.80×10^8	2308.65
	Results obtained through MOPSO algorithm									
1	4.77×10^6	4.84×10^6	9.98×10^6	7.33×10^7	1.87×10^8	2.15×10^8	3.76×10^5	3.90×10^5	7.50×10^5	222.64
2	1.05×10^7	1.20×10^7	2.76×10^7	8.54×10^7	3.00×10^8	1.91×10^9	8.78×10^6	8.92×10^6	1.15×10^7	1562.60
3	3.20×10^7	3.26×10^7	3.29×10^7	1.61×10^{10}	1.74×10^{10}	1.90×10^{10}	1.22×10^8	1.38×10^8	1.71×10^8	2145.18

The economic-minimal, environmental-minimal and social-maximal solution for the first case is analysed and presented in Table 3. This case is considered due to the small size of the data set. It can be observed from this Table 3 that if policymakers decide to optimise the economic objective over the environmental and social, the best option has an environmental objective of 2.09×10^8, the social objective of 3.91×10^5 and an economic objective of 4.73×10^6. Similarly, if policymakers want to optimise the environmental objective over the other two objectives, the values reported in the second row of Table 3 is the best option. Finally, the third row provides the best alternative for the optimisation of social objectives over the economic and environmental objectives. Unlike single-objective problems, here it is very difficult to find one single global optimal solution which can satisfy all three objectives simultaneously due to multiple objectives. Thus, the payoff matrix provides several options to policymakers while optimising one solution over another. Moreover, both algorithms provide a similar nature of Pareto fronts for all three considered cases, but the Pareto front obtained for the first case is portrayed in Figure 3 due to brevity. In the first case, MOGLNPSO found 11 non-dominated solutions, whereas MOPSO obtained nine solutions. The decision makers can select any solution among the given set of non-dominated solutions, and they can implement it to improve the sustainability performance of the FSCs.

Table 3 Payoff matrix of small case

Objective functions	Economic	Environmental	Social
Economic	$\mathbf{4.73 \times 10^6}$	2.09×10^8	3.91×10^5
Environmental	4.82×10^6	$\mathbf{7.28 \times 10^7}$	3.80×10^5
Social	9.96×10^6	1.84×10^8	$\mathbf{7.61 \times 10^5}$

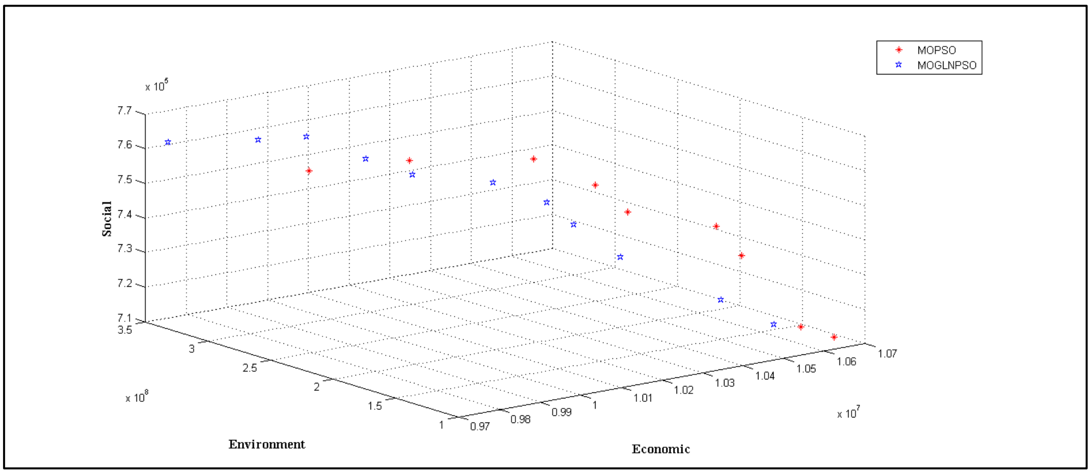


Figure 3 Pareto front of small case

Figure 3 Alt Text: 3-Dimensional scatter plot demonstrating Pareto front obtained using MOPSO and MOGLNPSO

6.1 Sensitivity analysis

Sensitivity analysis is conducted on the first case considering supply, demand and storage capacities of silos. Various acronyms used in figures while describing many components of three objectives in this subsection are mentioned as follows. SEC – Silo establishment cost, TRC – Transportation cost, INC – Inventory cost, TC – Total cost. ESE – Emission produced during silo construction, ETR – Transportation emission, EIN – Emission produced due to inventory, TE – Total emission. JC –Jobs created, BED – Balanced Economic development, FEWG – Farmers economic and welfare growth, PH – Public health and TSB –Total social benefits.

6.1.1 Impact of variation in supply and demand

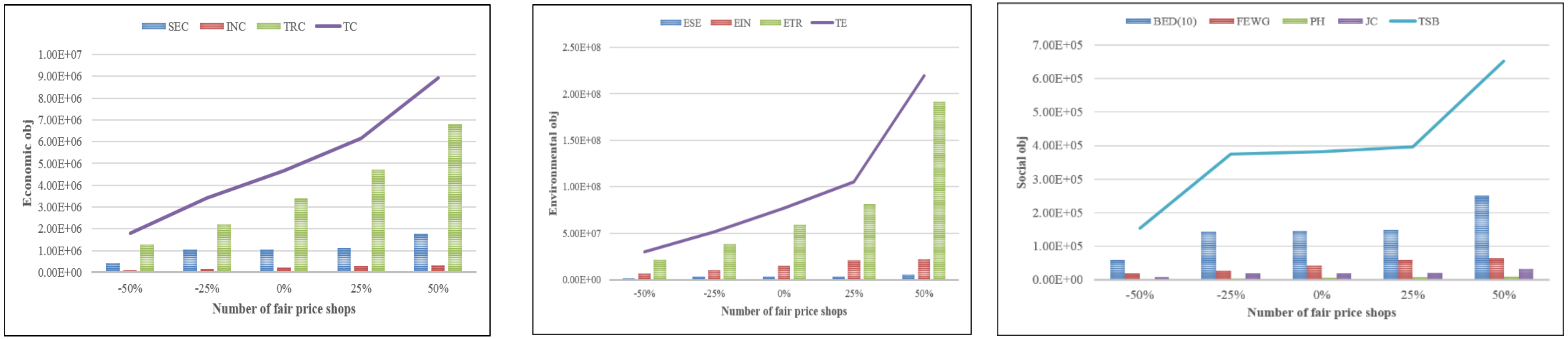
We have varied the number of procurement centres in the range of [-50%, +50%] of their current values and its impact on three objective functions is captured in Figures 4(a), (b) and (c). It can be observed from Figure 4(a) that increasing the number of procurement centres leads to a rise in the economic objective. As the number of procurement centres increases, the transportation emissions, which have a major share in the environmental objective increase up to a certain level and finally reduce due to the construction of additional base silos (Figure 4b). The number of constructed base silos increases after the rise of procurement centres to accommodate additional food stock. Therefore, the silo establishment cost (Figure 4a) increases after the increment of procurement centres. Figure 4(c) depicts the impact on the social objective function, including a number of job opportunities created, balanced economic development, economic welfare and growth level of farmers, and public health level. It is noticed from this figure as the number of procurement centres increases, the total shipment quantity between the first stage increases, which further leads to the establishment of additional silos. The fixed jobs opportunities rose due to the construction of additional silos; and increased food grain stock at silos has helped to raise the variable job opportunities to manage food grain stock. The quick movement of food grain stock from procurement centres to base silos enables surplus/free space at the procurement centre to procure more stock from farmers. Farmers can sell their yield to the nearby procurement centres and gain the advantage of MSP decided by the government organisations. This results in the improvement in economic and welfare growth of farmers. The balanced economic development of the under-developed region is enhanced after the establishment of silos in those regions. The public health level has not observed any impact of the variations in procurement centres because the demand for the fair price shops remains the same.

Correspondingly, the impact of the variation in a number of fair price shops on three objective functions is depicted in Figs. 5(a), (b) and (c). All components of economic objectives observed the growth of their numerical values as the fair price shops upsurge from -50% to +50%. To satisfy the demand of additional fair price shops, more shipment quantity is transferred from procurement centres to regional-level silos. This leads to incremental transportation costs and emissions. Additional silos are constructed to satisfy the demand of increased fair price shops. Thus, silo establishment cost gets escalated after the increment in fair price shops. Similar types of variation are perceived in the social objective components. The public health level of a particular region is enhanced because of the satisfaction of demand of additional fair price shops. The management authorities are likely to procure more food grain stock from farmers to satisfy the demand of increased fair price shops, which helps them to improve their economic and welfare growth. The additional silos constructed enhanced the balanced economic development of less developed regions. These silos and increased food grain stock may help to generate higher numbers of jobs.

(a) (b) (c)

Figure 4 Impact of procurement centres (supply) on (a) economic (b) environmental and (c) social objective

Figure 4 Alt Text: Cluster column charts illustrating the effect of procurement centres on three objectives



(a) (b) (c)

Figure 5 Impact of fair price shops (demand) on (a) economic (b) environmental and (c) social objective

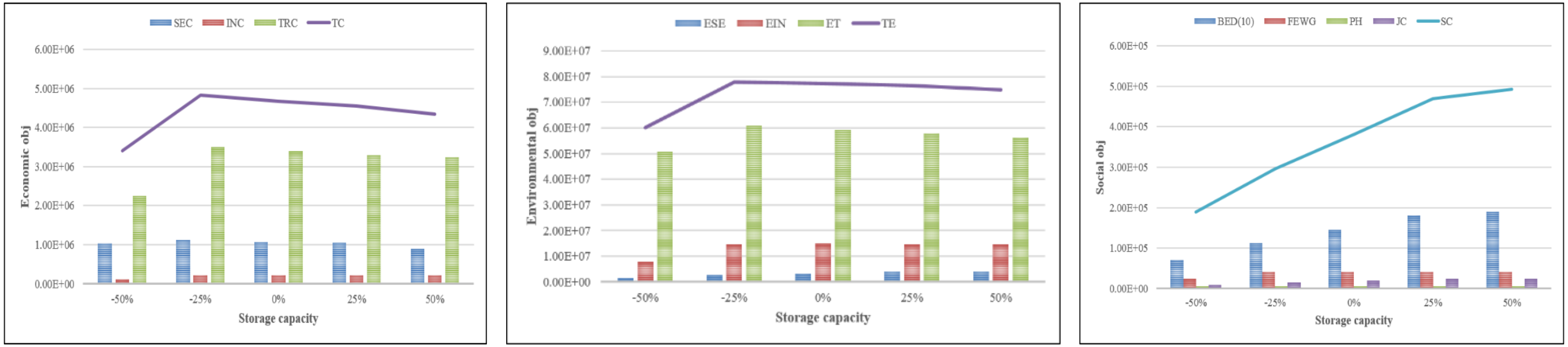
Figure 5 Alt Text: Cluster column charts displaying the effect of fair price shops on three objectives

6.1.2 Impact of variation in storage capacity of silos

The sensitivity analysis by changing the overall storage capacity of silos in the range [-50%, +50%] is carried out to inspect whether variations in storage capacity can be used for improvement in economic, environmental and social objectives. Fig. 6(a) represents the changes in economic objective function over a range of storage capacity levels. It is noticed that increasing the storage capacity results in reduced economic objective function values because of a reduction in transportation costs. The emission generated by silos is increased after the increment of storage capacity. Also, similar behaviour with minor augmentation is noticed for emissions generated due to inventory. Transportation emissions decline when storage capacity increases because vehicles need to travel less distance to reach the warehouses (Fig. 6b). In the case of the social objective, the increment in storage capacity impacts all major components of the social objective except public health level and, thus, maximises social benefit (Fig. 6c). The significant impact on balanced economic development, number of jobs created and farmer's economic growth level after the increment in capacity levels of silos is noticed from Fig. 6(c). The government agencies procure maximum stock from farmers due to the additional silos, which is advantageous in order to provide price support to a maximum number of farmers. The fixed and variable job opportunities are augmented after the construction of new silos in the under-developed provinces. This is beneficial to improve the balanced economic development of that region.

7. Concluding remarks and future scope

This research aimed to design a food supply chain network for enhanced social sustainability and enable policymakers in developing economies to make informed decisions. A multi-objective mixed integer non–linear programming model embracing all three dimensions of sustainability has been developed to support strategic and tactical decision making in FSCs. The quantification and integration of multiple social factors such as farmers' economic and welfare growth, balanced economic development, employment, and public health level as the third objective in the proposed mathematical model is unique (see Table 1). The novel elements in the mathematical model, especially in objective functions and constraints are explained in section 4.



(a) (b) (c)

Figure 6 Impact of silo storage capacity variations on (a) economic (b) environmental and (c) social objective

Figure 6 Alt Text: Cluster column charts demonstrating the effect of silo storage capacity on three objectives

The results presented in this study have been achieved by solving a mathematical model by means of two Pareto-based algorithms. The model is solved using the data collected from major food grain producing and consuming states in India. It is found that transport cost and related emission are the major contributors of economic and environmental objectives, respectively. However, balanced economic development has a major share in the social objective. The impact of supply, demand and the storage capacity of silos is evaluated by means of the sensitivity analysis. The economic and environmental objectives are significantly influenced by the demand parameter, compared with the other two model parameters. The majority of the entities in the social objective, such as balanced economic development, number of jobs created, and farmers' economic and welfare growth are significantly influenced by the storage capacity of silos. Various actors involved in the FSCs' operations like state government agencies, private logistics providers, railways and farmers can benefit from the insights evolved through the current study to improve the sustainability performance of FSC networks.

7.1 Theoretical implications

The study brings out several strong implications for the theory. The main theoretical contribution of this study lies in the integration and quantification of sustainability in the FSC network design context, with a particular focus on the social sustainability dimension. The economic and environmental impact of FSC activities has received huge attention (Banasik et al., 2019; Bortolini et al., 2018; Govindan, 2017; Seuring, 2013; Wang et al., 2018; Mohammed and Wang, 2017b; Brandenburg et al., 2014); however the social impact is weakly captured in the extant literature (Esteso et al., 2018; Zhu et al., 2018; Brandenburg et al., 2014, Kamble et al. 2020). The development of decision support models incorporating sustainability along with procurement, storage and transportation concerns are needed to enhance FSC performance in emerging economies (Asian et al. 2019, Esteso et al., 2018, Zhu et al., 2018). The development of a new decision support model for tackling SFSC network design issues is likely to fill this evident research gap associated with the integration and measurement of sustainability impact.

According to Zhu et al. (2018), there is a dearth of research in the improvement of profit of farmers in the FSC context. This literature gap is bridged by embedding farmers' economic and welfare growth in the social objective function. Furthermore, the majority of studies in the SFSC area have been conducted in developed economies, with only a few in the developing economies. Due to the complex structure of FSCs, consumer preferences and other varying factors, it may be difficult to transform models (and their findings) from developed to developing economies. The main focus of developing economies is on expanding food production to serve the ever-growing population and, thus, several studies ignore the environmental as well as societal impact (Shukla and Jharkharia, 2013). The underlying problem is inspired by the real-world scenario of the food grain supply chain network in India, which fills the aforementioned literature gap.

7.2 Managerial implications

Multiple stakeholders involved in FSC activities can benefit from the insights drawn in this study. Trade-offs between various dimensions of sustainability are crucial for the effectual management process of policymakers. Due to the geographically widespread locations of producing and consuming states, the transportation cost has a significant share in the economic objective. Hence, it needs special attention rather than other entities of economic objectives while establishing silos. Large initial capital investment is required for silo establishment; thus, the management authorities could utilise the proposed decision support model to conduct a viability analysis of the probable locations. The feasibility analysis helps to avoid the cost of a large investment outlay. The sensitivity analysis results reveal that policymakers need to construct a sufficient number of silos in producing and consuming states by maintaining a balance between TBL of sustainability. Speedy movement of food grains from procurement centres to silos would help to make available space at different storage facilities across the FSC network. This leads to the augmentation of procurement quantities and farmers obtaining benefits from the MSP decided upon by the government. This price support operation also helps to improve their economic and welfare condition. The wastage of food grain stocks at procurement centres due to open storage will be reduced after building new base silos. Furthermore, the construction of field and regional silos will be beneficial for satisfying the economically weaker section's demand for food grains. This helps to tackle malnutrition problems arising from the unavailability of healthy and nutritious food. The construction of silos opens several fixed job opportunities and movement of available inventory creates different variable jobs, which will be advantageous for resolving rising unemployment problems in developing economies like India.

Furthermore, the decision-makers will enhance the social impact of FSCs by establishing silos in less developed regions. This will further result in an increase in the number of jobs, which eventually leads to an overall improvement in underdeveloped regions. The members involved in the FSC process need to travel fewer distances due to the construction of new silos, which leads to a decrease in transportation costs and allied emissions. The lowered emissions reduce the carbon tax of transport operations. The optimal inventory level of food grain stocks at silos will be beneficial for decreasing emissions generated due to excess inventory stock. The policymakers can select any one solution among several non-dominated solutions as per their preference. The movement and storage plan of food grain stock for a definite planning horizon obtained through solving the model will be helpful for robust planning and coordination decisions. Furthermore, the existing storage facilities can be better utilised by means of an efficient storage activity plan. The rail mode of transportation can be used instead of a road to enable a reduction of transportation costs and CO_2 emissions. Some of the above highlighted impacts, particularly the focus on the holistic integration of social factors along with the other two dimensions of sustainability, can significantly influence managerial decision making for policymakers and several others involved (at strategic and tactical level) in managing FSC networks.

7.3 Limitations and future scope

Some of the limitations of the study, which could support driving future research are presented in this sub-section. The sensitivity analysis conducted in this study only focussed on key parameters and consideration of other parameters, especially environment and social, can provide micro-level perspectives on the overall performance of FSC networks. Economies of scale in transportation and water footprint were not integrated into the formulated model, which can be considered as a future research avenue. Moreover, this study dealt with only a single food grain commodity and did not focus on the quality degradation of food grains. The current study can be extended to scenarios associated with import and export opportunities for developing economies. Assessment results are based on a small case and a similar study could have been replicated on medium and large cases. However, due to limitations of time and access to data, this has not been conducted in this study. Less than truck-load scenarios and riverine transportation were not considered while formulating the mathematical model.

In this study, we assumed that the set of potential sites for the establishment of silos are well-known. Thus, it may be possible that policymakers take support for finding these sets of potential sites. The incorporation of perishability aspects, limited shelf life, quantification of post-harvest losses and application of the proposed model in other developing nations are other future avenues to extend this study. In order to capture the uncertainty associated with model parameters, future research can consider uncertain procurement and demand. Similarly, the focus on backlog and shortages are another two possible ways of developing the existing model. The current model can be extended to a multi-objective scenario by incorporating the minimisation of uncertain lead time/delivery time or maximisation of service level as a fourth or combined objective. The present study can be enriched by integrating the disruption scenarios or sustainable risk management in the proposed mathematical model. The consideration of end consumer sustainable predilections and their readiness to pay in the modelling are prominent research paths. The integration of energy consumption, food quality, and emissions are needed in food supply chain distribution models to control supply chains costs.

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Data Availability Statement:

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Alexandratos, Nikos, and Jelle Bruinsma. 2012. “World agriculture towards 2030/2050: the 2012 revision.” ESA Working paper No. 12-03. Rome, FAO.

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.

Alagusundaram, K. 2016. “Should India Consider Shifting to Bulk Food Grain Storage System? – A Conceptual Framework,” 431–437.

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 C. T. Sunil Kumar. 2018. “A Mathematical Model and Solution Methods for Rail Freight Transportation Planning in an Indian Food Grain Supply Chain.” *Sadhana - Academy Proceedings in Engineering Sciences* 43 (12).

Aras, Necati, and Ümit Bilge. 2018. “Robust Supply Chain Network Design with Multi-Products for a Company in the Food Sector.” *Applied Mathematical Modelling* 60: 526–539.

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.

Beske, Philip, Anna Land, and Stefan Seuring. 2014. “Sustainable Supply Chain Management Practices and Dynamic Capabilities in the Food Industry: A Critical Analysis of the Literature.” *International Journal of Production Economics* 152: 131–143.

Borodin, Valeria, Jean Bourtembourg, Faicel Hnaien, and Nacima Labadie. 2016. “Handling Uncertainty in Agricultural Supply Chain Management: A State of the Art.” *European Journal of Operational Research* 254 (2): 348–359.

Bortolini, Marco, Francesco Gabriele Galizia, Cristina Mora, Lucia Botti, and Michele Rosano. 2018. “Bi-Objective Design of Fresh Food Supply Chain Networks with Reusable and Disposable Packaging Containers.” *Journal of Cleaner Production* 184: 375–388.

Brandenburg, Marcus, Kannan Govindan, Joseph Sarkis, and Stefan Seuring. 2014. “Quantitative Models for Sustainable Supply Chain Management: Developments and Directions.” *European Journal of Operational Research* 233 (2): 299–312.

De, Arkajyoti, and Surya Prakash Singh. 2021. “Analysis of Fuzzy Applications in the Agri-Supply Chain: A Literature Review.” *Journal of Cleaner Production* 283.

Dhawan, Vibha. 2017. “Water and Agriculture in India: Background Paper for the South Asia Expert Panel during the Global Forum for Food and Agriculture - (GFFA) 2017.” *OAV - German Asia-Pacific Business Association,* 1–25. https://www.oav.de/fileadmin/user_upload/5_Publikationen/5_Studien/170118_Study_Water_Agriculture_India.pdf.

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* 56 (13): 4418–4446.

Etemadnia, Hamideh, Stephan J. Goetz, Patrick Canning, and Mohammad Sadegh Tavallali. 2015. “Optimal Wholesale Facilities Location within the Fruit and Vegetables Supply Chain with Bimodal Transportation Options: An LP-MIP Heuristic Approach.” *European Journal of Operational Research* 244 (2): 648–661.

Ghadge, Abhijeet, Merilena Kaklamanou, Sonal Choudhary, and Michael Bourlakis. 2017. “Implementing Environmental Practices within the Greek Dairy Supply Chain Drivers and Barriers for SMEs.” *Industrial Management and Data Systems* 117 (9): 1995–2014.

Ghadge, Abhijeet, Hendrik Wurtmann, and Stefan Seuring. 2020. "Managing Climate Change Risks in Global Supply Chains: A Review and Research Agenda." *International Journal of Production Research* 58 (1): 44–64.

Ghadge, Abhijeet, Merve Er Kara, Dnyaneshwar G. Mogale, Sonal Choudhary, and Samir Dani. 2021. Sustainability implementation challenges in food supply chains: A case of UK artisan cheese producers. *Production Planning & Control* 32, no. 14: 1191-1206.

Gholami-Zanjani, Seyed Mohammad, Mohammad Saeed Jabalameli, Walid Klibi, and Mir Saman Pishvaee. 2021. "A Robust Location-Inventory Model for Food Supply Chains Operating under Disruptions with Ripple Effects." *International Journal of Production Research* 59 (1): 301–324.

Govindan, Kannan. 2018. "Sustainable Consumption and Production in the Food Supply Chain: A Conceptual Framework." *International Journal of Production Economics* 195: 419–431.

Hosseini-Motlagh, Seyyed Mahdi, Maryam Johari, and Roza Zirakpourdehkordi. 2020. "Grain Production Management to Reduce Global Warming Potential under Financial Constraints and Time Value of Money Using Evolutionary Game Theory." *International Journal of Production Research*. doi:10.1080/00207543.2020.1773562.

Huang, Ji kun, and Yang jie Wang. 2014. "Financing Sustainable Agriculture under Climate Change." *Journal of Integrative Agriculture* 13 (4): 698–712.

Irani, Zahir, Amir M. Sharif, Habin Lee, Emel Aktas, Zeynep Topaloğlu, Tamara van't Wout, and Samsul Huda. 2018. "Managing Food Security through Food Waste and Loss: Small Data to Big Data." *Computers and Operations Research* 98: 367–383.

Jonkman, Jochem, Ana P. Barbosa-Póvoa, and Jacqueline M. Bloemhof. 2019. "Integrating Harvesting Decisions in the Design of Agro-Food Supply Chains." *European Journal of Operational Research* 276 (1): 247–258.

Krishnan, Ramesh, Renu Agarwal, Christopher Bajada, and K. Arshinder. 2020. "Redesigning a Food Supply Chain for Environmental Sustainability – An Analysis of Resource Use and Recovery." *Journal of Cleaner Production* 242.

Landrigan, Philip J., Richard Fuller, Nereus J.R. Acosta, Olusoji Adeyi, Robert Arnold, Niladri (Nil) Basu, Abdoulaye Bibi Baldé, et al. 2018. "The Lancet Commission on Pollution and Health." *The Lancet* 391 (10119): 462–512.

Mahapatra, Maheswar Singha and Biswajit Mahanty. 2018. "India's National Food Security Programme: A Strategic Insight." *Sadhana - Academy Proceedings in Engineering Sciences* 43 (12).

Maiyar, Lohithaksha M., and Jitesh J. Thakkar. 2020. "Robust Optimisation of Sustainable Food Grain Transportation with Uncertain Supply and Intentional Disruptions." *International Journal of Production Research* 58 (18): 5651–5675.

Mangla, Sachin Kumar, Sunil Luthra, Nick Rich, Divesh Kumar, Nripendra P. Rana, and Yogesh K. Dwivedi. 2018. “Enablers to Implement Sustainable Initiatives in Agri-Food Supply Chains.” *International Journal of Production Economics* 203: 379–393.

Mariappan, Karthikeyan, and Deyi Zhou. 2019. “A Threat of Farmers’ Suicide and the Opportunity in Organic Farming for Sustainable Agricultural Development in India.” *Sustainability (Switzerland)* 11 (8).

Martins, C. L., M. T. Melo, and M. V. Pato. 2019. “Redesigning a Food Bank Supply Chain Network in a Triple Bottom Line Context.” *International Journal of Production Economics* 214: 234–247.

Mogale, D. G., Naoufel Cheikhrouhou, and Manoj Kumar Tiwari. 2020. “Modelling of Sustainable Food Grain Supply Chain Distribution System: A Bi-Objective Approach.” *International Journal of Production Research* 58 (18): 5521–5544.

Mogale, D. G., Sri Krishna Kumar, and Manoj Kumar Tiwari. 2020. “Green Food Supply Chain Design Considering Risk and Post-Harvest Losses: A Case Study.” *Annals of Operations Research* 295 (1): 257–284.

Mohammed, Ahmed, and Qian Wang. 2017. “The Fuzzy Multi-Objective Distribution Planner for a Green Meat Supply Chain.” *International Journal of Production Economics* 184: 47–58.

Mohebalizadehgashti, Fatemeh, Hossein Zolfagharinia, and Saman Hassanzadeh Amin. 2020. “Designing a Green Meat Supply Chain Network: A Multi-Objective Approach.” *International Journal of Production Economics* 219: 312–327.

Nourbakhsh, Seyed Mohammad, Yun Bai, Guilherme D.N. Maia, Yanfeng Ouyang, and Luis Rodriguez. 2016. “Grain Supply Chain Network Design and Logistics Planning for Reducing Post-Harvest Loss.” *Biosystems Engineering* 151: 105–115.

Ritchie, Hannah, David Reay, and Peter Higgins. 2018. “Sustainable Food Security in India—Domestic Production and Macronutrient Availability.” *PLoS ONE* 13 (3): 1–17.

Rohmer, S. U.K., J. C. Gerdessen, and G. D.H. Claassen. 2019. “Sustainable Supply Chain Design in the Food System with Dietary Considerations: A Multi-Objective Analysis.” *European Journal of Operational Research* 273 (3): 1149–1164.

Sgarbossa, Fabio, and Ivan Russo. 2017. “A Proactive Model in Sustainable Food Supply Chain: Insight from a Case Study.” *International Journal of Production Economics* 183: 596–606.

Sharma, Rohit, Sachin S. Kamble, Angappa Gunasekaran, Vikas Kumar, and Anil Kumar. 2020. “A Systematic Literature Review on Machine Learning Applications for Sustainable Agriculture Supply Chain Performance.” *Computers and Operations Research* 119.

Shrivastava, RK, 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): 69–77.

Shukla, Manish, and Sanjay Jharkharia. 2013. “Agri-Fresh Produce Supply Chain Management: A State-of-the-Art Literature Review.” *International Journal of Operations and Production Management* 33 (2): 114–158.

Singh, Sube, Ramesh Kumar, Rohit Panchal, and Manoj Kumar Tiwari. 2021. “Impact of COVID-19 on Logistics Systems and Disruptions in Food Supply Chain.” *International Journal of Production Research* 59 (7): 1993–2008.

Soto-Silva, Wladimir E., Esteve Nadal-Roig, Marcela C. González-Araya, and Lluis 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.

Utomo, Dhanan Sarwo, Bhakti Stephan Onggo, and Stephen Eldridge. 2018. “Applications of Agent-Based Modelling and Simulation in the Agri-Food Supply Chains.” *European Journal of Operational Research* 269 (3): 794–805.

Validi, Sahar, Arijit Bhattacharya, and P. J. Byrne. 2014. "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.

Varsei, Mohsen, and Sergey Polyakovskiy. 2017. “Sustainable Supply Chain Network Design: A Case of the Wine Industry in Australia.” *Omega* 66. Elsevier: 236–247.

Zhao, Guoqing, Shaofeng Liu, Carmen Lopez, Huilan Chen, Haiyan Lu, Sachin Kumar Mangla, and Sebastian Elgueta. 2020. “Risk Analysis of the Agri-Food Supply Chain: A Multi-Method Approach.” *International Journal of Production Research* 58 (16): 4851–4876.

Zhao, Xiaofei, Ping Wang, and Raktim Pal. 2021. “The Effects of Agro-Food Supply Chain Integration on Product Quality and Financial Performance: Evidence from Chinese Agro-Food Processing Business.” *International Journal of Production Economics* 231 doi:10.1016/j.ijpe.2020.107832.

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* 56 (17): 5700–5722. doi:10.1080/00207543.2018.1425014.

Appendix A

Notations of mathematical model

Notations

Sets	**Definition**	**Indices**	**Description**
I	Set of procurement centres	i	Procurement centres
J	Set of potential locations for establishing base silos	j	Base silos
K	Set of potential locations for establishing field silos	k	Field silos
L	Set of potential locations for establishing regional silos	l	Regional silos
M	Set of fair price shops	m	Fair price shops
N	Set of capacity levels of base silos	n	Capacity levels of base silos
P	Set of capacity levels of field silos	p	Capacity levels of field silos
Q	Set of capacity levels of regional silos	q	Capacity levels of regional silos
R	Set of vehicle type available at procurement centres	r	Vehicle type available at procurement centres
S	Set of rake type available at base silos	s	Rake type available at base silos
U	Set of rake type available at field silos	u	Rake type available at field silos
V	Set of vehicle type available at regional silos	v	Vehicle type available at regional silos
T	Set of time periods	t	Time periods

Technical parameters	**Description**
d_{ij}	Distance between procurement centre i to base silo j (km)
d_{jk}	Distance between base silo j to field silo k (km)
d_{kl}	Distance between field silo k to regional silo l (km)
d_{lm}	Distance between regional silo l to fair price shops m (km)
A_i^t	Amount of food grain stock available at purchase centre i in time period t (MT)
D_m^t	Demand of food grain of fair price shop m in time period t (MT)
$scap_{jn}$	Storage capacity of base silo j with capacity level n (MT)
$scap_{kp}$	Storage capacity of field silo k with capacity level p (MT)
$scap_{lq}$	Storage capacity of regional silo l with capacity level q (MT)
α_r	Capacity of vehicle type r (MT)
α_s	Capacity of rake type s (MT)
α_u	Capacity of rake type u (MT)

α_v	Capacity of vehicle type *v* (MT)
ω_{ri}^t	Number of *r* type of vehicles available at procurement centre *i* in period *t*
ω_{sj}^t	Number of *s* type of rakes available at base silo *j* in period *t*
ω_{uk}^t	Number of *u* type of rakes available at field silo *k* in period *t*
ω_{vl}^t	Number of *v* type of vehicles available at regional silo *l* in period *t*
Φ	A very large number

Economic parameters	**Description**
fc_{jn}	Fixed cost of establishing a base silo with capacity level *n* at location *j* (USD)
fc_{kp}	Fixed cost of establishing a field silo with capacity level *p* at location *k* (USD)
fc_{lq}	Fixed cost of establishing a regional silo with capacity level *q* at location *l* (USD)
a	Unit variable transportation cost of food grain by road mode (USD/km)
b	Unit variable transportation cost of food grain by rail mode (USD/km)
e_j	Unit inventory holding cost per period at base silo *j* (USD/period)
e_k	Unit inventory holding cost per period at field silo *k* (USD/period)
e_l	Unit inventory holding cost per period at regional silo *l* (USD/period)

Environmental Parameters	**Description**
εo_{jn}	Amount of emission generated to establish a base silo *j* with capacity level *n* (gco2)
εo_{kp}	Amount of emission generated to establish a field silo *k* with capacity level *p* (gco2)
εo_{lq}	Amount of emission generated to establish a regional silo *l* with capacity level *q* (gco2)
εt_{ij}^r	Amount of emission generated per unit distance for each *r* type of vehicle travelling from procurement centre *i* to base silo *j* (gco2)
εt_{jk}^s	Amount of emission generated per unit distance for each *s* type of rake travelling from base silo *j* to field silo *k* (gco2)
εt_{kl}^u	Amount of emission generated per unit distance for each *u* type of rake travelling from field silo *k* to regional silo *l* (gco2)
εt_{lm}^v	Amount of emission generated per unit distance for each *v* type of vehicle travelling from regional silo *l* to fair price shops *m* (gco2)
εi_j	Amount of emission generated for holding the one metric ton inventory of food grain per period at base silo *j* (gco2)

εi_k	Amount of emission generated for holding the one metric ton inventory of food grain per period at field silo *k* (gco2)
εi_l	Amount of emission generated for holding the one metric ton inventory of food grain per period at regional silo *l* (gco2)

Social parameters	**Description**
jc_{jn}	The number of fixed job opportunities created if base silo *j* is established with capacity level *n*
jc_{kp}	The number of fixed job opportunities created if field silo *k* is established with capacity level *p*
jc_{lq}	The number of fixed job opportunities created if regional silo *l* is established with capacity *q*
mhc	The monthly food grain stock handling capacity of worker
ue_j	Unemployment rate of the region where base silo *j* is to be established
ue_k	Unemployment rate of the region where field silo *k* is to be established
ue_l	Unemployment rate of the region where regional silo *l* is to be established
π_{jn}	Economic value of established base silo *j* with capacity level *n*
π_{kp}	Economic value of established field silo *k* with capacity level *p*
π_{lq}	Economic value of established regional silo *l* with capacity level *q*
ϕ_j	Regional development of location *j* where base silo is to be established
ϕ_k	Regional development of location *k* where field silo is to be established
ϕ_l	Regional development of location *l* where regional silo is to be established
ξ_i	The economic welfare and growth rate of farmers assigned to the procurement centre *i*
ψ_m	The nutrition level of people buying food grains from fair price shops *m*
γ_{jc} and γ_{be}	The weight of created job opportunities and balanced economic development
γ_{ewg} and γ_{ph}	The weight of economic welfare and growth rate of farmers, and public health

Decision Variables

Binary variables

X_{jn} 1 if a base silo with capacity level *n* is established at potential location *j;* 0 otherwise

Y_{kp} 1 if a field silo with capacity level *p* is established at potential location *k;* 0 otherwise

Z_{lq} 1 if a regional silo with capacity level *q* is established at potential location *l;* 0 otherwise

W_{ij}^{t} 1 if the procurement centre *i* is assigned to base silo *j* during time period *t;* 0 otherwise

W_{jk}^{t} 1 if base silo *j* is assigned to the field silo *k* during time period *t;* 0 otherwise

W_{kl}^{t} 1 if field silo *k* is assigned to the regional silo *l* during time period *t;* 0 otherwise

W_{lm}^{t} 1 if the regional silo *l* is assigned to the fair price shops *m* during time period *t;* 0 otherwise

Continuous variables

E_{ij}^{t} Amount of food grain dispatched from procurement centre *i* to base silo *j* during time period *t*

F_{jk}^{t} Amount of food grain dispatched from base silo *j* to field silo *k* during time period t

G_{kl}^{t} Amount of food grain dispatched from field silo *k* to regional silo *l* during time period *t*

H_{lm}^{t} Amount of food grain dispatched from regional silo l to fair price shops *m* during time period *t*

inj_{j}^{t} Amount of food grain stock available in the base silo *j* at the end of period *t*

ink_{k}^{t} Amount of food grain stock available in the field silo *k* at the end of period *t*

inl_{l}^{t} Amount of food grain stock available in the regional silo *l* at the end of period *t*

Integer variables

ρ_{ij}^{rt} Number of *r* type of vehicles used for food grain transportation between procurement centre *i* to base silo *j* during period *t*

Δ_{jk}^{st} Number of *s* type of rakes used for food grain transportation between base silo *j* to field silo *k* in time period *t*

β_{kl}^{ut} Number of *u* type of rakes used for food grain transportation between field silo *k* to regional silo *l* in time period *t*

μ_{lm}^{vt} Number of *v* type of vehicles used for food grain transportation between regional silo *l* to fair price shops *m* in time period *t*