A Mathematical Model to Minimize the Total Cost in Apple Fruit Supply Chain: The Case of Indian Scenario

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Abstract. Apple cultivation is a major employment and extremely successful economic activity in the Kashmir valley (India). The apple supply chain (ASC) in India is conventional and entails value loss at many levels of the supply chain (SC), which raises the cost of the final product. With increased production comes increased challenges in the ASC, such as a lack of suitable storage, a shortage of processing equipment, a lack of packing material, inefficient transportation, and middleman manipulation. Efficient apple transportation reduces post-harvest loss and stabilizes prices at regional cold storage facilities which is critical. The aim of this article is to develop the simple Indian ASC to ensure food security for all by means of affordability. A mathematical model is formulated to design a simple Indian ASC to minimize the total distribution cost (TDC) and post-harvest loss. A real case study of Baramulla District (India) apple distribution is solved using the heuristic approach to check the validity of the formulated model.

Keywords: Apple supply chain · Mathematical model · Heuristic approach · Food security

1 Introduction

India, with 11.3% of the world's agricultural land, has been cited as the world's top producer of numerous agricultural products [1]. The nation's economic growth is primarily driven by agricultural productivity and farmer profitability. India recorded high fruits and vegetable production of 305.4 million tons in the year 2017–2018 [2]. However, the Indian fruit supply chain (FSC) is not lucrative for farmers since they do not even receive half of what customers pay [3, 4]. This is due to the inefficient movement of products in the FSC [5]. Another important issue in FSC is high post-harvest losses, accounting for 15–25% of total production. This is because of an inadequate SC structure, a lack of post-harvest management methodologies, and poor product transportation [6].

India is the second largest producer of fruits (64 MT) accounting for 10% of world fruit production [7] and the apple produced about 2814.31 ('000) MT in the year 2019–2020 [2]. According to IIHR, the total loss of apples is 12.26%, including farm operations and storage loss [8]. The key issues in the Indian ASC are 1) losses during transit and storage; and 2) a lack of adequate technology, innovative techniques; 3) a lack of

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understanding of apple flow; 4) a lack of transparency in the SC; 5) monitoring and traceability; 6) less control over food safety and quality across the SC; 7) Short shelf-life period; 8) Farmers' lack of understanding and knowledge 9) a lack of cold storage infrastructure [9].

Thus, this paper aims to design a simple ASC to minimize total distribution costs thereby increasing farmers' profitability and affordability to the customers. Studying apple SC's omnipresent environment will aid in managing the price of apple for end consumers and decreasing waste for the stakeholders. In this paper, we present a mathematical formulation that identifies the potential location and allocation of procurement centers (PC) and refrigerated distribution centers (DC). The proposed multi-stage model is validated further by applying it to a real-world case study of the ASC in the Indian district of Baramulla, Kashmir.

2 Literature Review

Numerous mathematical models have been reviewed for planning and organizing input variables for fresh fruit supply chains, with integer linear programming being the most widely used [10, 11]. The citrus supply chain is addressed by a linear programming model to maximize total profits [12] and to determine the possible location and number of facilities required to establish a closed-loop citrus supply chain network by taking environmental and economic factors into account [13]. Similarly, a MILP model is employed to calculate quality loss and harvesting costs for grapes in wine production [14]. The logistics decisions of fruit among retailers have been addressed by developing integrated methods [15]. A linear programming model is developed to minimize the transportation costs of fruit from hubs to processing plants [16].

The food supply chain has been empirically examined in the Indian context by considering perishability [17, 18] and the major limitations and issues in designing an Indian FSC were identified [4, 19]. Ans SC model is suggested to minimize post-harvest losses during logistics caused by respiration and CO2 emissions from the fruits in India [20]. A perishable food supply chain review shows that constructing the SC network model for developing nations like India received less attention [21, 22]. Gardas et al. [6, 23] modeled and evaluated casual factors of post-harvest losses in Indian FSC. Mir et al. [24] figured out the distribution hierarchy with respect to the costs and limitations of the apple industry. Wani and Mishra [25], formulated a mathematical model to maximize the profit of the apple orchards while controlling emissions and degradation effectively.

According to these studies, much research work has been directed into the study of FSC, especially apple, and researchers have disregarded the mathematical modeling and design of the ASC in the Indian context. It is observed that the ASC is inefficient for the farmers owing to low profit. As a result, it is regarded crucial to develop a mathematical model to plan and construct the simple Indian ASC to minimize the total distribution costs.

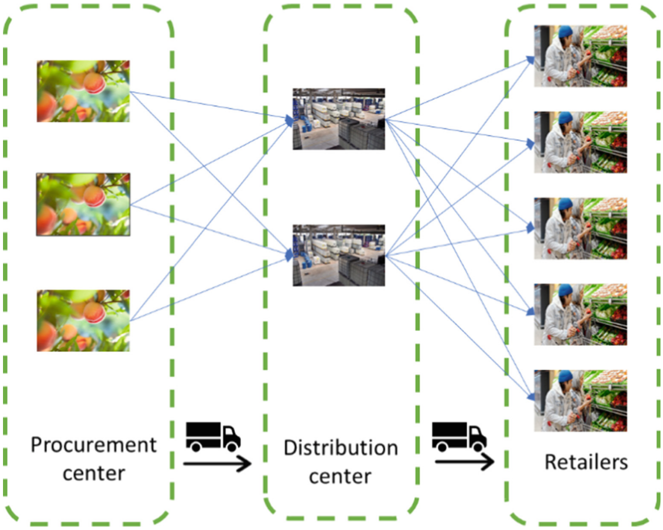

Fig. 1. Simple Indian ASC network

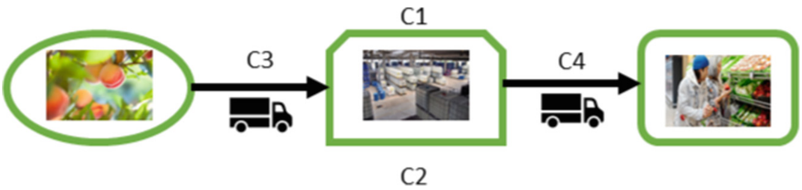

Fig. 2. The cost incurred in the ASC

3 A Simple Apple Supply Chain Model

In this section, we formulate a three-echelon (PCs, DCs, and CZs), a multi-period mathematical model of simple Indian ASC to represent the flow of apples from procurement centers to customer zones (CZ).

The structure of the simple Indian ASC is shown in Fig. 1. Farmers grow apples and bring their apples to the procurement centers (PC). Wholesalers purchase these apples by bidding the highest price possible depending on quantity and quality. Thereafter, the apples are graded and sorted in the distribution centers (DC) and then sold to retailers in small quantities. Finally, the retailers will sell to the customers. Hence, the model is formulated for the simple SC of apple shipment from PCs to CZs via DCs.

Figure 2 shows the costs incurred in the model of ASC considered. C1 represents the fixed cost of opening DCs. C2 represents inventory holding cost at DCs. C3 denotes the transportation costs from PCs to DCs. C4 indicates the transportation costs from DCs to CZs.

In the model, apples from PCs to DCs and from DCs to CZs are transported through a reefer truck. Apples are transported from DCs to CZs to satisfy the local demand. A mathematical model is developed to minimize total distribution cost (TDC) to ensure the affordability of the end consumers' and farmers' profit by considering the single mode of transportation. It is assumed that the excess apples are stored at DCs and 3% of apples are exported [26] after satisfying the local demand. As a result, a suitable inventory equation at DC is added to the model to sustain inventory flow. In each period, the developed model selects the best location and allocation of DCs from a set of available prospective locations. This model also determines the amounts of apples sent between these locations and the inventory levels at DCs in each period.

4 Mathematical Modeling

The proposed mathematical model is a modified version of the agricultural supply chain [5]. The major modifications include (i) the supply data of apples being calculated to the real-world scenario and the demand data being calculated to ensure food security (ii) the assumption of 2% of food loss while harvesting and 3% of apples exported in the SC (iii) excess apples are stored in the DC (iv) no food loss in the model (v) DC is considered to be refrigerated and vehicle used is reefer truck.

4.1 Assumptions

(1) Apple availability in the PCs, CZs' local demand, and various cost parameters are known.
(2) The total supply is greater than or equal to the total demand in each period.
(3) Only DCs store excess items.
(4) Time taken for transportation is considered nil.
(8) Vehicle used for transportation is considered a reefer truck.
(9) 2% loss is assumed while harvesting.
(10) no food loss in the model due to the technology implementation.

4.2 Notations

P index of PCs, $p \in P$

w index of DCs, $w \in W$

r index of CZs, $r \in R$

t index of time periods (days), $t \in T$

Parameters:

S_p^t quantity of apple available at PC_p for the period t (kg)

D_r^t local demand at CZ_r for the period t (kg)

$D1_{pw}$ distance from PC_p to DC_w (km)

$D2_{wr}$ distance from DC_w to CZ_r (km)

TC_1 unit transportation cost including refrigeration cost from PC to DC (INR/km/kg)

TC_2 unit transportation cost including refrigeration cost from DC to CZ (INR/km/kg)

HC_w holding cost of apple at DC_w (INR/kg/period)

LB_w lower bound capacity of DC_w (kg)

UB_w upper bound capacity of DC_w (kg)

NDnumber of DCs to be opened

FC_w fixed cost of opening DC_w (INR)
Q^t_{pw} quantity of apple transported from PC_p to DC_w in period t (kg)
Q'^t_{wr} quantity of apple transported from DC_w to CZ_k in period t (kg)
I^t_w inventory of apple at DC_w in period t after satisfying local demand and export (kg)
E^t_w export quantity of apple at DC_w in period t after satisfying demand (kg)
Decision variables:
H^t_w 1 if DC_w is opened in period t; 0 otherwise.
Objective function:

$$\text{Minimize } Z = C1 + C2 + C3 + C4 \quad (1)$$

$$C1 = \sum_{t=1}^{T} \sum_{w=1}^{W} FC_w H^t_w \quad (a)$$
$$C2 = \sum_{t=1}^{T} \sum_{w=1}^{W} HC_w I^t_w \quad (b)$$
$$C3 = \sum_{t=1}^{T} \sum_{p=1}^{P} \sum_{w=1}^{W} D1_{pw} TC_1 Q^t_{pw} \quad (c)$$
$$C4 = \sum_{t=1}^{T} \sum_{w=1}^{W} \sum_{r=1}^{R} D2_{wr} TC_2 Q'^t_{wr} \quad (d)$$

Subject to:

$$\sum_{w=1}^{W} Q^t_{pw} = S^t_p, \ \forall p, \ \forall t \quad (2)$$

$$\sum_{p=1}^{P} Q^t_{pw} \le UB_w H^t_w, \ \forall w, \ \forall t \quad (3)$$

$$\sum_{r=1}^{R} Q'^t_{wr} \le \sum_{p=1}^{P} Q^t_{pw}, \ \forall w, \ \forall t \quad (4)$$

$$\sum_{w=1}^{W} Q'^t_{wr} \ge D^t_r, \ \forall r, \ \forall t \quad (5)$$

$$I^{t-1}_w + \sum_{p=1}^{P} Q^t_{pw} - \sum_{r=1}^{R} Q'^t_{wr} - E^t_w = I^t_w, \ \forall w, \ \forall t \quad (6)$$

$$\sum_{w=1}^{W} H^t_w = N, \quad \forall t \quad (7)$$

Constraint (2) assures that fruits are transferred from PCs to any DC based on their availability. Constraint (3) guarantees that apples are only moved from PCs to opened DCs and that the number received in DCs does not exceed the upper bound limit of that DC. Constraint (4) regulates apple flow conservation at each DC. Constraint (5) ensures that the number of apples provided to each CZ is higher than or equal to the local demand. Constraint (6) governs inventory balance for consecutive periods at each DC. Constraint (7) guarantees the total number of DCs that can be opened.

5 Proposed Methodology

The mathematical model has been solved using the heuristic approach and flowchart of the algorithm is shown in the Fig. 3.

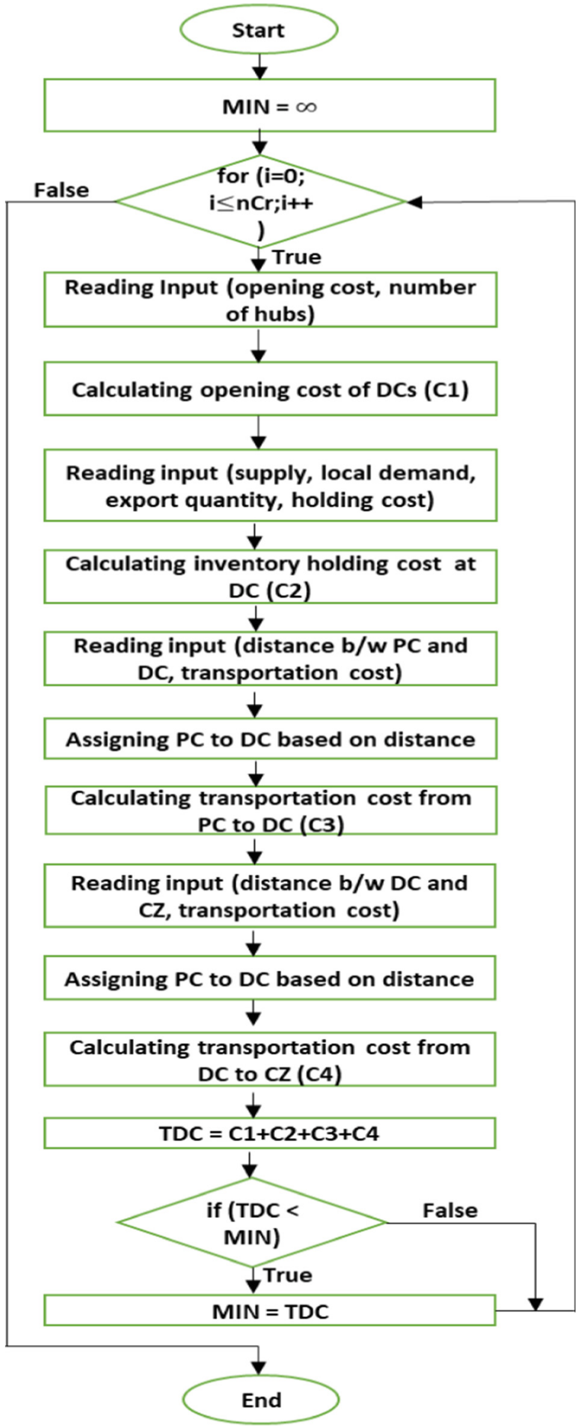

Fig. 3. Algorithm flowchart of heuristic approach

The supply, local demand, transportation cost, holding cost, opening cost, distance between PC and DC, distance between DC and CZ, percentage of export quantity are given as input into the algorithm. The algorithm has been written to find out the minimum value of the TDC. The number of combinations of 8 DCs is 28. Therefore, the algorithm is set into the 'for loop' for 28 combinations of DCs to find the minimum TDC.

6 Real-World Case Analysis

We compare and assess the feasibility of the formulated model using a case study scenario from Baramulla (District of Jammu & Kashmir, India). Kashmir is India's leading apple producer, with about 89% of its horticultural acreage dedicated to apple growing. Kashmir has the privilege of producing 2026.47 ('000) MT of high-quality apples in the year 2019–2020 [27]. Baramulla district in Kashmir has the highest production of apples in the same year with a quantity of 479570 metric tons [27].

In Baramulla district, there are 48 villages [28]. In this work, we assume each village has many farmers and these farmers bring their produced apples to the PCs and its location as a PC's location. We considered 8 major locations as potential DC locations to serve all the CZs in order to ensure food security. Baramulla district has 8 tehsils [29] and we consider these tehsils having 3 retailers (CZ) each. Distance from PCs to DCs and from DCs to CZs are determined using Google maps.

The number of apples requested by a CZ is determined by 100 g of apple intake per person per day and the CZ population [30]. The estimated values are used to compute the average supply and demand for all PCs and CZs for a single period. Based on current conditions, the fixed cost of operating a DC, unit transit cost from PC to DC and DC to CZ, and holding cost at DC are assumed. The values of supply based on the production of apple in the year 2019–2020 and demand based on population in the Baramulla district is shown in the Table 1.

The production of apple in Baramulla district in the year 2019–2020 was found to be 4,79,570 metric tons. The harvesting season of apple is from August to November. The production of apple per day is considered as 39,96,416 kg. The food loss is considered as 2% before it reaches the PC and the quantity available at PCs is 39,16,487 kg. It is assumed that each PC has the same quantity of apple to initiate the supply chain

Table 1. Estimated value of supply and demand

Supply, S_p^t (kg/period/PC)	**Demand, D_r^t (kg/period/CZ)**
PC1 – PC48 - 81593	CZ1 – CZ3 - 3,410 CZ4 – CZ6 - 3,088 CZ7 – CZ9 - 2,419 CZ10 – CZ12 - 2,232 CZ13 – CZ15 - 7,639 CZ16 – CZ18 - 4,988 CZ19 – CZ21 - 7,330 CZ22 – CZ24 - 2,496

Table 2. Cost associated with different parameters

Parameter	Value
Fixed cost of opening DC	50,000 INR
Transportation cost (per kg/km) From PC to DC, TC_1 From DC to CZ, TC_2	1 INR 1 INR
Holding cost for each DC (per kg/period), HC_W	5 INR
Upper bound limit of each DC (Metric tonnes/period), UB_W	4,000 Mts
Export quantity of apple after satisfying demand (%/period), E_w^t	3%

Table 3. Allocation of PCs and CZs to the DCs

DC	PC	CZ
DC 2	PC2,PC6,PC11,PC18,PC20,PC21,PC23, PC30,PC32,PC34,PC39,PC42,PC44,PC48	CZ4-CZ6,CZ8,CZ9, CZ13-CZ15,CZ24
DC4	PC1,PC3-PC5,PC7-PC10,PC12-PC17,PC19,PC22,PC24-PC29, PC31,PC33,PC35-PC38,PC40,PC41,PC43,PC45-PC47	CZ1-CZ3,CZ7,CZ10-CZ12, CZ16-CZ23,

flow. The demand data is calculated from the population of each tehsil. It is assumed that 100 g of apple is needed for each person in the district and the total demand is estimated as 1,00,804 kg. The cost of various parameters is assumed very close to the practical scenario. The export quantity of apple is 3% in the year 2021–2022 [26]. The vehicle considered for the transportation is reefer truck. The cost associated with DC is considered with refrigeration (Table 2).

7 Results and Discussion

To minimize the cost of opening DCs to a minimum, we considered only two DCs to be opened. The decision to open a DC is influenced by supply and local demand, as well as the distance between DCs and other nodes in subsequent phases. From the results, it is observed that, transportation costs play a vital role in deciding the final price of the apples. The excess quantity stored in DC after satisfying the demand and export can be distributed to the remaining parts of the India. The optimized TDC is obtained when DC 2 and 4 are opened when time period is considered as one day. And it is noted that DC 2 and 4 holds the minimum costs when the time period is increased and remaining parameters are kept constant. The PCs and CZs assigned to DC 2 and DC 4 are given in Table 3.

Also, refrigerated DCs and refrigerated trucks are being used in this model to ensure the food safety by maintaining apple quality throughout the SC with the help of technologies like internet of things and blockchain. The consideration of refrigerated DC and reefers truck in the model will ensure food safety and therefore food loss is minimized throughout the SC. If TDC is minimized in the SC, then the affordability of the apple increases at the customer end. This affordability will ensure the food security in India to increase its rank in GHI.

8 Conclusion and Future Scope

Inefficient Indian ASC results in low farmer profitability and considerable post-harvest losses. The formulation of the mathematical model for the ASC has not been documented in the literature. In this research, we develop a mathematical model of a simple Indian ASC. Three-echelon, multi-period is designed to reduce TDC in the chain. The model calculates the location of DCs, the quantity of apples transported from PCs to DCs and from DCs to CZs, and the inventory levels at each DC. In addition, a case study problem from the Baramulla (India) is solved using the heuristic approach to compare and validate the proposed model. To the best of the author's knowledge, this work is the first attempt to design and develop simple Indian ASC. This research would aid in comprehending ASC execution and will serve as a resource for all policymakers and SC partners in meeting challenges, developing new action plans and strategies. This model can be improved by relaxing assumptions one by one and adding more SC members. For example, demand and quantity available at PC data could be more precise and the number of DC opened could be more than two. The real time data from the IoT and blockchain technologies can be integrated into the mathematical model to address the real scenario challenges.

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