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Enhancing Profitability in Multi-Fruit Supply Chains Using Multi-Temperature Refrigerated Vehicles

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ABSTRACT

The agricultural cold chain is multifaceted compared to other supply chains due to the perishability, demand and price variations, food safety and food quality, and its reliance on climate situation. Though utilization of cold chain infrastructure decreases food loss and enhances food security, it will also lead to an increase in total supply chain cost, further reducing the stakeholder's profit. This makes the stakeholders in the FSC hesitate in implementing cold chain storage and logistics. To overcome this challenge, this paper aims to maximize the profit of the intermediate stakeholder by considering multi-temperature refrigerated vehicles (MTRV) along the fruit supply chain (FSC). A mixed integer non-linear programming (MINLP) mathematical model is proposed to maximize the profit in the fruit supply chain network (FSCN) that involves a state distribution center (SDC), district distribution center (DDC), and retailers. The developed mathematical model is solved using the heuristic approach. Many scenarios were built and tested to evaluate the formulated model's efficiency. The results show that the profit of the intermediate stakeholder in the FSC is appreciable while considering MTRV instead of dedicated reefer trucks.

1. Introduction.

Distribution organizations have to deal with the difficult situation of attempting to both increase their revenues and decrease their operational expenses due to growing competition. To accomplish this challenging goal, it is crucial to comprehend how different components of the supply chain may be effectively interconnected to generate value for the organization (Alinezhad et al., 2022). Wholesalers or distributors of perishable commodities in the cold chain industry encounter the challenge of making optimal decisions on product pricing and order quantities from suppliers, to maximize overall net profit (Mejía et al., 2021). The cold chain refers to the temperature-controlled supply chain that includes the storage, transportation, and distribution of perishable products. It plays a vital role in extending the product shelf life and minimizing the amount of food waste generated. The cold chain of agricultural foods like fruits is complex due to its short shelf life, high fluctuations in demand and prices, increasing consumer concerns for food safety and quality, and its dependence on climate conditions (Vorst and Beulens, 2002). The most important element in the cold chain is transportation where the temperature of the product must be maintained depending on the ambient temperature (Prabhu et al, 2019). To overcome this challenge cold transport operations, entail the transportation of commodi-

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ties utilizing railcars, refrigerated cargo ships, reefers, and air cargo while ensuring the necessary temperature and humidity conditions are maintained. Reefers are a collective term used to refer to many types of temperature-controlled transportation units, such as vans, light trucks, and containers (Hsu and Chen, 2014). Typically, reefers are customized to cater to a certain food product and its accompanying temperature needs. Modern truck types are outfitted with temperature-controlled compartments, enabling the transportation of several products in separate partitions within a single reefer vehicle. When distribution centers order several food items from the same wholesalers, the utilization of multi-temperature refrigerated vehicles (MTRVs) enables the delivery of diverse product categories simultaneously on a single truck (Hübner and Ostermeier, 2019).

When it comes to logistics operations, the implementation of cold chain infrastructure will increase the transportation cost and operational cost further increasing the total supply chain cost. This makes the intermediate stakeholders think about implementing cold storage and refrigerated logistics operations in terms of profit. Therefore, this study aims to maximize the profit of a proposed three-echelon multi-fruit cold chain network considering MTRV. A mathematical model is proposed considering key cost components including transportation cost, operational cost, inventory cost, and refrigeration cost. The model captures the complexities associated with handling multiple fruit types with varying temperature requirements across different echelons of the supply chain. To efficiently solve the formulated problem, a heuristic approach is employed, enabling the analysis of large-scale and realistic problem instances within a reasonable computational time.

2. Literature Review.

In recent times, the agricultural food business, namely fresh fruits, has gained recognition and attention as a crucial factor for profitability in supply chains (Lucas and Chhajed, 2004). In 2011, Zhang and Wilhelm introduced an intriguing version of mathematical models for the FSC sector. In contrast, a literature review on the production of fresh food, including fruits, flowers, and vegetables, was published by Shukla and Jharkharia (2013) by covering two decades from 1991 to 2011. Mathematical models for agricultural supply chains and FSCs have also been the subject of several research projects. To maximize the fruit's freshness, Amorim et al. (2012) investigated the distribution network of perishable foods. To develop fresh and processed fruit supply chains, Verdouw et al. (2010) developed a simple model to minimize the total cost.

Etemadnia et al. (2015) devised a facility location problem solution in FSC with two transportation alternatives and a heuristic approach to determine the best location for a wholesale facility. Nadal-Roig and Plà-Aragonés (2015) proposed an integer linear programming model to optimize the daily transportation of fruit from distribution centres to treatment plants. The developed model minimizes the expenses associated with transportation. Consequently, they suggested an innovative operational optimization technique to decrease the number of truck trips made each day. Haider & Choubey (2025) introduced a new fresh FSC to the field of operational research models. Additionally, they critically evaluate a huge volume of literature pertaining to the FSC. They highlighted several issues in the fresh fruit supply chain, including extended supply lead time and supply-demand imbalance. Javanmardan et. al., (2024) designed a perishable food supply chain network considering fruit quality, prices, distribution modes, perishability rate, and recycling process. They developed a mixed-integer linear programming (MILP) problem and examined a real case study. Sahebjamnia et al. (2020) devised an innovative multi-objective integer non-linear programming model to minimize costs related to waste, transportation, and inventory while maximizing the profit in a citrus supply chain network.

Kim and Park (2020) examined the efficacy of multi-unit trucks as a substitute for standard single-temperature reefers in last-mile transportation between hubs and merchants. Mohammadi et al. (2023) presented a framework that combines the advantages of dynamic and multi-compartment routing to achieve sustainable, effective, and efficient waste management techniques. A large neighborhood search approach is applied to the extended multi-compartment vehicle routing problem model in a grocery distribution (Frank et al., 2021; Sahu et al., 2023). Wang et al. (2023) developed a mathematical model to address the multi-compartment electric vehicle routing problem. This model considered factors such as time windows, temperature, and humidity settings and it is solved using a hybrid approach that includes adaptive large neighborhood search and tabu search heuristic strategy.

It is noted from the literature that the design of FSCN is limited and the formulation of a mathematical model to maximize the profit from the stakeholder perspective is very limited. It is observed that the utilization of MTRV in FSC is also very limited. Therefore, this study proposes a MINLP mathematical model considering MTRV in FSC to maximize the profit of the intermediate stakeholder.

3. Mathematical Formulation.

The fruit supply chain network (FSCN) considering MTRV consists of three levels: State Distribution Centres (SDC), District Distribution Centres (SDC), and Retailers is shown in figure 1.

Figure 1: Multi-fruit supply chain network considering MTRV.

Source: Authors.

The SDCs procure a variety of fruits from different states and transport the fruits to the nearby DDCs. Then the DDCs transport the combination of fruits to the retailers based on the demand. In general, the variety of fruits are transported in a non-refrigerated truck or dedicated reefer truck that can accommodate single fruit with optimum temperature. Utilization of non-reefer truck leads to shorter shelf life of the fruits which further results in food loss and decrease in profit. On the other hand, considering dedicated reefer truck will increase the shelf life and the total cost incurred is also increased as well that further decreases the supply chain profit. Therefore, it is proposed to consider MTRV which carries a variety of fruits with different optimum temperature at one instance. As shown in Figure 1, MTRV considered between SDC and DDC comprises of two compartments whereas MTRV considered between DDC and retailer comprises of three compartments. Likewise, the MTRV can be utilized depending on the demand at DDC and retailer. The profit can be maximized by minimizing the total cost incurred in the supply chain rather than relying on increasing sales revenue. The optimum location of DDC and the optimum vehicle routing plays an important role in minimizing the total cost of the supply chain. Therefore, the mathematical model is formulated to maximize the profit considering MTRV by optimizing facility allocation and vehicle routing.

3.1. Assumptions.

- The amount of fruits handled at each SDC and DDC, along with their storage capacities, are predetermined and deterministic.
- DDC's potential locations are identified in advance and remain fixed.
- The supply of fruits is sufficient to fulfil all demand requirements.
- Excess inventory is allowed to be held only at the DDCs.

3.2. Notations.

3.2.1. Index Sets.

j index of SDCs, i ∈ I

m index of DDCs, k ∈ K

r index of RTs, l ∈ L

t index of time periods (days), t ∈ T

f index of fruits, f ∈ F

w vehicle available at SDCs

y vehicle available at DDCs

FC_m	Fixed cost associated with operating DDC m
$TC1$	Transportation cost from SDC j to DDC m
$TC2$	Transportation cost from DDC m to retailer r
FC_w	Fixed cost of operating vehicle type w
FC_y	Fixed cost of operating vehicle type y
HC_{jf}	Holding cost at SDC j for type fruit f
HC_{mf}	Holding cost at DDC m for type fruit f
OC_f	Operational cost associated with type fruit f
RC_w^f	Refrigeration cost for transporting fruit type f between SDC j and DDC m
RC_y^f	Refrigeration cost for transporting fruit type f between DDC m and retailer r
$D1_{jk}$	Distance between state distribution centre j to district distribution centre m
$D1_{ml}$	Distance between district distribution centre m and retailer r
U_{jm}^{wt}	Travel time of vehicle type w from SDC j to DDC m during time period t
U_{mr}^{yt}	Travel time of vehicle type y from DDC m and retailer r during time period t
A_{jf}^t	Quantity of fruit type f available at SDC j during time period t
Cap_m	Storage capacity of DDC m
Cap_w^f	Carrying capacity of vehicle type w for fruit combination f
Cap_y^f	Carrying capacity of vehicle type y for fruit combination f
d_j^{ft}	Demand for fruit type f at retailer r during period t
α_{jw}	Total number of available vehicles of type w at SDC j
β_{my}	Total number of available vehicles of type y at DDC m
SP_{fm}	Selling price of fruit type f at DDC m

X_m	1 if district distribution centre m is established 0 otherwise
x_{jm}^w	1 if vehicle w is used between state distribution centre j to district distribution centre m 0 otherwise
x_{mr}^y	1 if vehicle y is used between district distribution centre m to retailer r 0 otherwise
Q_{jm}^{ft}	Amount of fruit type f shipped from SDC j to DDC m during period t
Q'^{ft}_{mr}	Amount of fruit type g shipped from DDC m to retailer r during period t
N_{jm}^{wt}	Number of vehicles of type w deployed between SDC j and DDC m in period t
N_{mr}^{yt}	Number of vehicles of type y deployed between DDC m and retailer r in period t
Z_m^{ft}	Inventory of fruit type f available at DDC m at the end of period t

3.3. Objective function.

Maximize profit = Total revenue – Total cost (Transportation, Inventory holding, Operational and Refrigeration)

$$\text{Total revenue} = \sum_{j\in J}\sum_{m\in M}\sum_{f\in F}\sum_{t\in T} SP_{fm}\cdot Q_{jm}^{P,ft} \tag{1}$$

$$\begin{aligned}\text{Transportation cost} = &\sum_{j\in J}\sum_{m\in M}\sum_{f\in F}\sum_{t\in T} D1_{jm}\,TC1\,Q_{jm}^{ft}\\ &+\sum_{t\in T}\sum_{w\in W}\sum_{j\in J}\sum_{m\in M} FC_w\,N_{jm}^{wt}\\ &+\sum_{m\in M}\sum_{r\in R}\sum_{f\in F}\sum_{t\in T} D2_{mr}\,TC2\,Q_{mr}^{ft}\\ &+\sum_{t\in T}\sum_{y\in Y}\sum_{m\in M}\sum_{r\in R} FC_y\,N_{mr}^{yt}.\end{aligned} \tag{2}$$

$$\text{Inventory holding cost} = \sum_{m\in M}\sum_{f\in F}\sum_{t\in T} HC_{mf}\,Z_m^{ft} \tag{3}$$

$$\begin{aligned}\text{Operational cost} = &\sum_{m\in M} FC_m\, X_m \\ &+ \sum_{j\in J}\sum_{m\in M}\sum_{f\in F}\sum_{t\in T} Q_{jm}^{ft}\, OC_f \\ &+ \sum_{m\in M}\sum_{r\in R}\sum_{f\in F}\sum_{t\in T} Q_{mr}^{ft}\, OC_f.\end{aligned} \tag{4}$$

$$\begin{aligned}\text{Refrigeration cost} = &\sum_{j\in J}\sum_{m\in M}\sum_{w\in W}\sum_{f\in F}\sum_{t\in T} RC_w^f\, x_{jm}^w\, U_{jm}^{wt} \\ &+ \sum_{m\in M}\sum_{r\in R}\sum_{f\in F}\sum_{y\in Y}\sum_{t\in T} RC_y^f\, x_{mr}^y\, U_{mr}^{yt}.\end{aligned} \tag{5}$$

3.4. Constraints.

$$\sum_{m\in M} Q_{jm}^{ft}.X_{jm}^{ft} \le A_{jf}^t \quad \forall j\in J,\ \forall f\in F,\ \forall t\in T \tag{6}$$

Fruits quantity shipped from SDC to DDC must not exceed the available inventory at SDC for the given period.

$$\sum_{r\in R} Q'^{ft}_{mr} \le Z_m^{ft} \ \ \forall m,\ \forall t \tag{7}$$

Fruits quantity shipped from DDC to the retailer must not exceed the maximum inventory available at the DDC in the given period.

$$\sum_{m\in M} Q'^{ft}_{mr} = d_r^{ft} \ \ \forall r,\ \forall t \tag{8}$$

Fruits quantity transported from all DDCs must satisfy the demand of each retailer.

$$Cap_m \ge \sum_{f\in F} Z_m^{f(t-1)} + \sum_{j\in J}\sum_{f\in F} Q_{jm}^{ft}.X_{jm}^{ft}\ ,\ t>1 \qquad \forall m,\ \forall t \tag{9}$$

At each DDC, the total of the previous period's inventory and the newly received fruit quantities must remain within its storage capacity limit.

$$Z_m^{ft} = Z_m^{f(t-1)} + \sum_{j\in J} Q_{jm}^{ft}.X_{jm}^{ft} - \sum_{m\in M} Q'^{ft}_{mr}.X_{mr}^{ft}\ , \quad t\ge 1\ \ \forall m,\ \forall f,\ \forall t \tag{10}$$

For each DDC, the ending inventory in a given period is determined by adding the previous period's inventory to the incoming fruit quantities and subtracting the quantity dispatched during that period.

$$\sum_{m\in M}\sum_{f\in F} Q_{jm}^{ft}.X_{jm}^{ft} \le \sum_{w\in W}\sum_{f\in F} N_{jm}^{wt}.Cap_w^f \tag{11}$$

$$\sum_{r\in R}\sum_{f\in F} Q'^{ft}_{mr}.X_{mr}^{ft} \le \sum_{y\in Y}\sum_{f\in F} N_{mr}^{yt}.Cap_y^f \tag{12}$$

The quantity of fruits transported from SDC and DDC is constrained by the carrying capacity of the refrigerated vehicles.

$$\sum_{w\in W} N_{jm}^{wt} \le \alpha_{jw}\ \forall w, \forall j, \forall m \tag{13}$$

$$\sum_{y\in Y} N_{mr}^{yt} \le \beta_{my}\ \forall y, \forall m, \forall r \tag{14}$$

The number of trucks deployed at each SDC and DDC is constrained by the total number of trucks available at the corresponding echelon.

4. Methodology.

A heuristic methodology is developed to efficiently solve the proposed model. Initially, input fields like cost associated with different parameters, DDC capacity, truck capacity, distance between SDC and DDC, distance between DDC and retailer, supply quantity, demand quantity, number of DDC to be operated are fed. Then, combinations are built to find the number of DDCs to be operated from the potential locations of DDCs. Finally, optimization of vehicle routing considering MTRV is done to increase the profit of the DDCs considered. The detailed procedure of heuristic algorithm is given below.

Step 1: Start the algorithm.

Step 2: Accepting input (cost associated with different parameters, DDC capacity for different fruits, truck capacity for different fruits, distance between SDC and DDC, distance between DDC and retailer, supply quantity, demand quantity, number of DDC to be operated, box capacity of fruits, selling price of the fruits).

Step 3: Initializing the objective function (maximizing profit).

Step 4: Generating maximum number of combinations for the number of DDCs to be operated considered.

Step 5: Sorting the DDCs with respect to the distance between SDC and DDC and the distance between DDC and retailers for the first combination generated.

Step 6: Calculating the number of trucks utilized between SDC and DDC, DDC and retailers and costs associated to the expenses and the profit.

Step 7: Store the value.

Step 8: Repeat the procedure from step 5 to step 7 for all the combinations generated.

Step 9: Replace the stored value if minimum value is generated.

Step 10: Stop the algorithm.

5. Parameters setting.

Table 1 shows the supply and demand data of various fruits of SDC and retailers respectively. To show the complexity of the model, problems in different sizes are designed. The efficiency of the proposed algorithm is evaluated by comparing the model to several instances of different sizes.

Table 1: Assumed supply and demand ranges.

Fruit	Available quantity per SDC (kg)	Required quantity per retailer (kg)
Apple	180 – 240	35 – 60
Mango	180 – 250	35 – 60
Pomegranate	80 – 160	35 – 55
Grapes	70 – 120	25 – 40
Orange	75 – 125	25 – 60

Source: Authors.

Table 2: Assumed Values of Model Parameters.

Model Parameters	Assumed values
Fixed operating cost of a DDC, FC_m	1000 USD
Transportation cost: SDC to DDC (TC_1)	1 USD (per kg/km)
Transportation cost: DDC to retailer (TC_2)	1 USD (per kg/km)
Cost of Holding Inventory at DDC, HC_{mf}	1 – 3 USD (per kg/period)
Handling/Operational cost at DDC for fruit type f, OC_f	2 – 5 USD
Storage limit of DDC per fruit, Cap_m	50 – 100 (metric tonnes/period)
Cost of type w vehicle, FC_w	5000 - 7000 USD
Cost of type y vehicle, FC_y	5000 - 7000 USD
Load capacity of vehicle type w for fruit f, Cap_w^f	8 tonnes
Load capacity of vehicle type y for fruit f, Cap_y^f	6 tonnes
Refrigeration cost for fruit in vehicle type w, RC_w^f	21 – 30 USD
Refrigeration cost for fruit in vehicle type y, RC_y^f	30 – 21 USD
Travel time for vehicle type w (SDC to DDC), U_{jm}^{wt}	Distance between SDC and DDC ÷ average speed of vehicle type w
Travel time for vehicle type y (DDC to retailer), U_{mr}^{yt}	Distance between DDC and retailer ÷ average speed of vehicle type y
Typical operating speed of vehicle types w and y	12 – 18 mph

Source: Authors.

Table 2 summarizes the parameter values used in the developed model. Each scenario is defined by the operation of number of SDCs, DDCs, and retailers, as well as the number of partitions allocated within the transport vehicles across different echelons. The details of different scenarios built is mentioned in Table 3.

Table 3: Details of built scenarios.

Problem instance	SDC	DDC	Retailer	MTRV considered between SDC and DDC	MTRV considered between DDC and Retailer
5-2-10	5	2	10	1	1
	5	2	10	2	2
	5	2	10	3	3
	5	2	10	2	3
	5	2	10	3	2
9-3-16	9	3	16	1	1
	9	3	16	2	2
	9	3	16	3	3
	9	3	16	2	3
	9	3	16	3	2
12-5-24	12	5	24	1	1
	12	5	24	2	2
	12	5	24	3	3
	12	5	24	2	3
	12	5	24	3	2

Source: Authors.

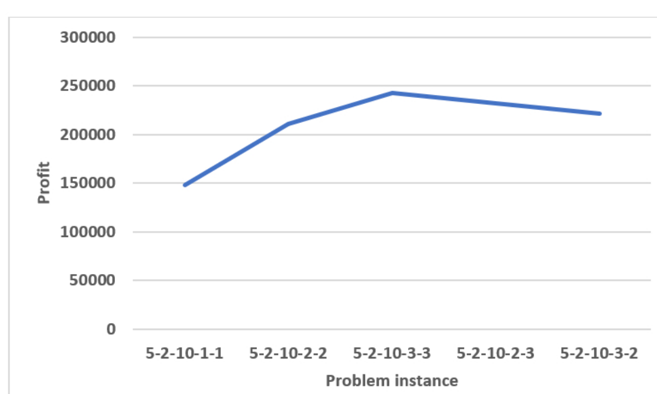
The number of partitions in the truck is assumed to be a maximum of three for all the scenarios. The combinations have been developed in the partitions of the truck starting from one (dedicated truck) to three partitions (MTRV).

6. Results and Discussion.

The figures 2, 3, and 4 display the profits earned in three distinct scenarios.

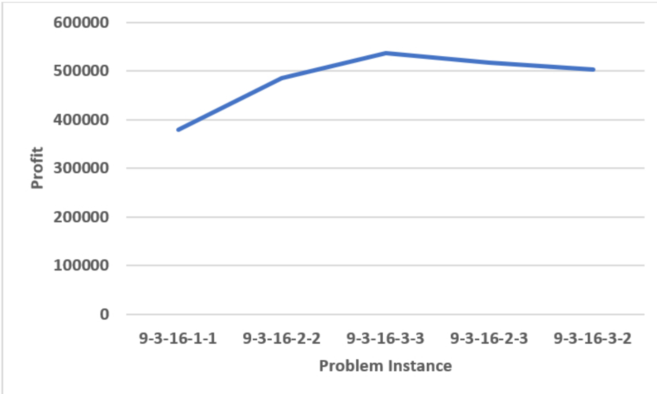
The profit exhibits a progressive increase across all scenarios from instance 1 to instance 3, followed by a subsequent decrease from instance 3 to instance 5. Using three partition trucks between the echelons has been seen to lead to an increase in profit, whereas using a dedicated reefer truck results in a decrease in profit. It is interesting to note that employing either 2 partitions or 3 partitions between the echelons results in a profit rise, although it does not surpass the profit generated by a 3-partition truck.

Figure 2: Profit generated for different instances in scenario 1.



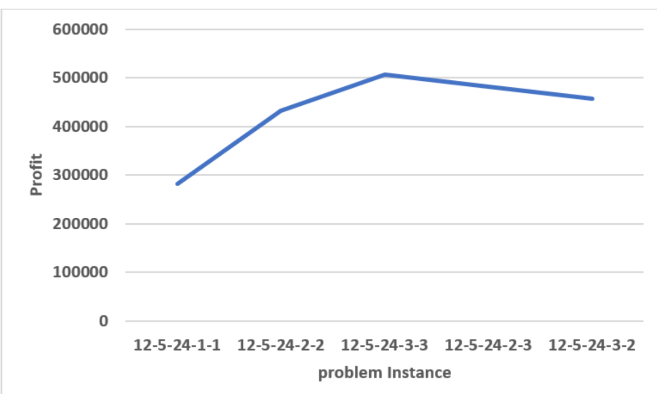
Source: Authors.

Figure 3: Profit generated for different instances in scenario 2.



Source: Authors.

Figure 4: Profit generated for different instances in scenario 3.



Source: Authors.

It is noted that the transportation cost included in the mathematical model is crucial for maximising the profit. The utilization of MTRV reduces the number of trucks required for transportation between echelons, resulting in a significant and immediate impact on profit. From the stakeholder's perspective, reduction in number of trucks would be a great advantage where the fixed cost for buying the trucks as well as the variable cost of transporting the goods is reduced. Another important factor in the mathematical model for maximizing profit generated is DDC's capacity. The number of refrigerated trucks operated and the transportation cost depends on DDC capacity.

The utilization of MTRV not only increases the stakeholders' profit but also reduces the cost of the fruits and thereby increasing affordability. Since all fruits are stored and transported at its optimum temperature, the food loss is reduced thereby improving food safety. Therefore, food security is also improved by enhancing its pillars - food safety and affordability. Additionally, utilization of MTRVs minimizes the food waste which in turn minimizes the emissions.

Conclusions.

FSC becomes complex when cold chain infrastructure is implemented to store and transport the fruits to increase their shelf life. The utilization of cold storage and refrigerated trucks will lead to decrease in profit for the stakeholders especially who owns and deals with the fruits warehouse and logistics. To overcome this challenge, this study proposes a MTRV model for the abovementioned stakeholder to maximize their profit in cold chain. A mathematical model is formulated considering three supply chain entities in the FSCN. The proposed model is addressed using heuristic solution method. Its effectiveness is assessed by developing and examining a range of different scenarios. The utilization of MTRV maximizes the stakeholder profit in all the scenarios. The profit reaches its peak when 3 partition reefer trucks are utilized between the echelons. The utilization of MTRVs not only maximizes profit of the stakeholders but also improves food security. It is achieved by improving food safety by maintaining each fruit in its optimum temperature and enhances food security by increasing affordability to the customers. The study has its own limitations by not considering other costs like cost of opening SDC and DDC, refrigeration cost during loading and unloading, and static nature of the model developed. The work can be extended by overcoming the above-mentioned limitations one by one and also by adding more number of entities to FSCN.

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