Designing a Distribution Plan for Perishable Produce in a Cold Chain Based Upon Final Quality at Destination

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Abstract

Maintaining a proper quality during export of perishables is a challenging issue as they degrade rapidly ones harvested. Hence, cold chain export is adopted. In order to deliver fresh and high-quality products to the end customer appropriate temperature-controlled distribution must be ensured. The current study targets 'distribution at destination' part of the cold chain taking into account the produce quality degradation. An optimization problem is formulated for minimizing the total cost of distribution of temperature sensitive perishables so that the desired quality produce reaches the customer in consumable condition. The temperature dependent overall quality of the produce is determined from a computational fluid dynamics (CFD) simulation and Kinetic rate law model. The cold chain export of an Indian mango variety namely 'Alphonso' from India to Singapore has been illustrated as a case study. The results show that the developed distribution plan can assure the fulfilment of customer prerequisites at lowest cost.

Keywords
Cold Chain, CFD, Overall Quality, Perishables Distribution planning and optimization.

1. Introduction
One of the major goals of export industries is to ensure that the produce reaches the destination and the end customers in acceptable condition, on time, with minimum cost. This becomes more challenging for perishable produce, including fruits, vegetables, dairy products, meat and fish products, as they tend to degrade ones harvested or processed. The rate of degradation of produce depends upon various internal and external factors and time period up to which it is subjected to those parameters. One of the major factors is surrounding temperature. The perishable demands to be kept in a temperature-controlled environment (Manouchehri et al. 2020). Failing to maintain the required temperature may result in rapid degradation, spoilage, growth of pathogens which makes the produce inedible. Almost one-third of all the food produced for consumption is wasted. Such large amount of wastage is quite inadmissible considering overall growing population and land resource constraint.

During the export of these perishables, the whole supply chain needs to be temperature controlled. This gives rise to the concept of cold chain export which involves application of a series of refrigeration steps along a supply chain so as to keep the perishables in desired temperature range (Mercier et al. 2017). Along with this, temperature inside the transport vehicles, refrigerated container and storage house should be monitored continuously. A lot of new wireless temperature monitoring technologies are available for the above-mentioned purpose. Various researches also have suggested the use of virtual temperature monitoring techniques like computational fluid dynamics (CFD) (Delele et al. 2013; Han et al. 2015; Pham et al. 2021). Prior knowledge of temperature condition of perishables can be helpful in predicting the quality and hence remaining shelf life of the perishables, in-transit as well as at the destination.

The final stage of cold chain is distribution of produce to end consumers ones it reaches the destination. Cold chain management logistics also concerns with efficient distribution of produce at destination (Hsiao et al. 2017). The perishable produces require temperature controlled warehouse and vehicles for storage and transportation (Keizer et al. 2015; Wei et al. 2019). These vehicles are generally more costly and consume more fuel than regular transport vehicles due to refrigeration equipment. Inclusion of these controls adds extra cost of road shipping, fuel expenditure for refrigeration and strict time limits to avoid excess quality deterioration (Mejjaouli and Babiceanu 2018; Wei et al. 2019). Furthermore, a single shipment may present large variations in quality among the produce, as different zones inside the refrigerated container are exposed to different surrounding conditions. A distribution plan must take into account the consumer requirement of food quality and also quick dispatch of the perishables with minimum shelf life so as to minimize the wastage. Along with this the total cost of storage and transport should also be minimum.

1.1. Objectives

The current study analyses the quality degradation of perishable produce in a typical cold chain export process, and develops a plan for distribution at destination, by ensuring the deliverables reach the retailer or customer in desired quality level, within specific time window and at lowest distribution cost. The export of an Indian mango variety, named *'Kesar'*, to Singapore, is considered here for case study. The temperature dependant quality of the mangoes with respect to time is determined from computational fluid dynamics (CFD) simulation and Kinetic rate law model.

2. Literature Review

A study was conducted to develop a model for cold chain distribution planning considering the customer pre-approved quality level and the distribution cost. For solving the problem, a biogeography-based optimization algorithm was proposed. Two case studies considering chilled meat distribution was considered (Hsiao et al. 2017). Another research focusses on the hub allocation problem which taking account of the quality decay of the product. A MILP model is combined with a hybrid optimization simulation approach for generating a cost optimal network design under product quality requirements (Keizer et al. 2015). Yet in another study, various mathematical and heuristic solution approach are developed to investigate the effect of integrating production scheduling and distributing on total costs and quality of delivered products. The model is validated by real settings of a catering company located in Denmark (Farahani and Grunow 2012). A stepwise analytical framework was developed for perishable products to preserve their quality throughout supply chain network. Initially a data driven quality prediction model was established, followed by development of a vehicle routing schedule and inventory quality targets so as to minimize the cost. Finally, the environmental control factors are optimized to ensure desired product quality. To validate the model the framework was applied to apple supply chain process (Xu et al. 2020). A detailed study to integrate product quality decay and heterogeneity in a network design model was performed. A mixed integer programming problem was formulated to maximize the profit under quality constraints. Finally, it was concluded that the heterogeneity in product quality decay should be taken into account in network design as it has a great influence on supply chain processes (Keizer et al. 2017). A mixed integer linear programming model was developed for production routing, considering produce quality and optimum temperature. The aim of the study was to calculate the production and supply amount for each time period, and distribution strategy for retailers (Manouchehri et al. 2020). Another study which takes into account and solves a real world problem of cold chain distribution in Yangtze River Delta of China with the help of mixed integer programming model, descriptive model and genetic algorithm (Wei et al. 2019). A vehicle routing problem is addressed for the case of frozen food delivery so as to minimize the delivery cost. The model was solved by genetic algorithm (Zhang and Chen 2014). In another study, the authors developed location-inventory routing model for perishable products which was also solved by genetic algorithm (Hiassat et al. 2017). A multi-period, multi-perishable product problem of perishables was proposed where the objective was to minimize total cost while preventing the stock outs. The model was solved using population-based simulated annealing algorithm (Shaabani and Kamalabadi 2016).

3. Methods

This study designs a distribution plan after the produce reaches its destination taking into account the cold chain export of *'Kesar'* mango from India to Singapore. The following steps define the methodology of distribution planning.

Step 1: Development of CFD model. A CFD model of entire cold chain is developed considering its different nodes.
Step 2: Simulation is performed, by including the thermal and physical properties of *'Kesar'* mango and by applying various initial conditions, to obtain the temperature distribution inside the entire domain.
Step 3: Quality evaluation: A temperature based overall quality with respect to time is predicted with the help of kinetic rate law model.
Step 4: An optimization problem is formulated to minimize the total cost of transportation taking into account the variation in quality of mangoes, and the distance to which the mangoes are to be shipped.
Step 5: The model is solved to obtain an optimized distribution plan.

3.1. Mathematical Model

In this problem, a single refrigerated warehouse, with unlimited capacity, directs the produces to multiple consumers or retailers, as shown in Figure 1. The capacity and storage cost of the warehouse is neglected. The produce is transported via multiple refrigerated vehicles from the warehouse to the destination. The type and speed of different refrigerated vehicles are assumed to be same and traffic congestion is neglected. The location and demands of the customer or the retailer are known. The quality decay of the perishables in-transit is incorporated into the model. The various model parameters are defined as follows:

q − Different qualities of mangoes
x_{ij} − Quantity of mango of quality i for customer j in kg
d_j − Distance of customer j
c_t − Unit cost of transportation
D_j − Demand of customer j
S_i − Supply of quality i
T_i − Time of degradation of ith quality mango
v − Velocity of vehicle
M − Large constant

The mathematical model is described below:

Minimize

$$Z = \sum_{j=1}^{J} \sum_{i=1}^{q\epsilon(q_1,q_2,\dots,q_n)} (x_{ij}) d_j c_t$$

Subject to

Demand constraint:

$$\sum_{j=1}^{J} x_{ij} \geq D_j$$

Supply constraint:

$$\sum_{i=1}^{q\epsilon(q_1,q_2,\dots,q_n)} x_{ij} \leq S_i$$

Constraint for quality assurance

$$z_{ij} = T_i - \frac{d_j}{v}$$

$$y_{ij} = 0 \; if \; z_{ij} \leq 0$$

$$y_{ij} = 1 \; if \; z_{ij} > 0$$

Difference between time for degradation and time to transport to customer j if greater than 0 then only select that customer

$$x_{ij} \leq M y_{ij}$$

Non-Negativity Constraint:

$$x_{ij}, d_j, D_j, S_i, T_i \geq 0$$

3.2. Cold Chain Export of Indian Mango

Cold chain of perishable products refers to the food supply chain that uses continuous circulation of cold air to maintain a suitable temperature and humidity for products, such as fruits, vegetables, dairy, meats, fish etc. Right after harvesting of fresh fruits or vegetables, the degradation process starts. The main post processing parameter affecting quality degradation is the temperature (Gogou et al. 2015).

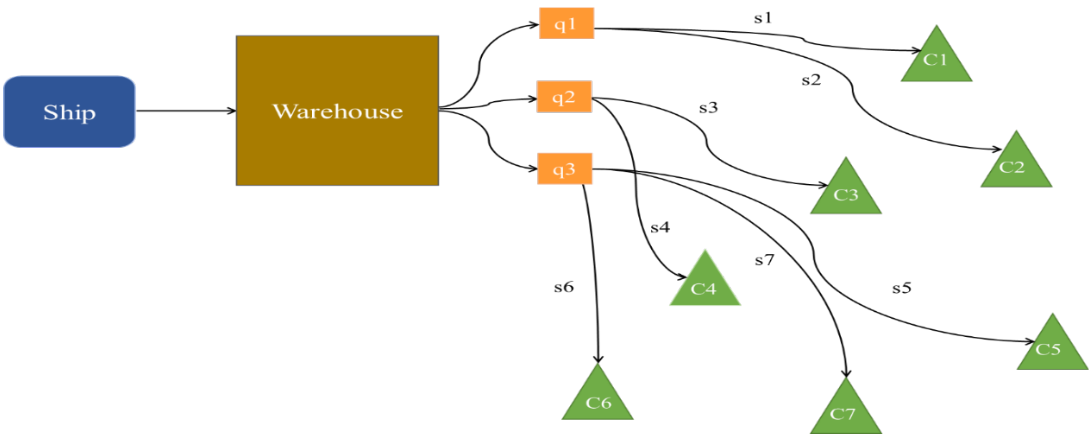


Figure 1. Overview of distribution of warehouse

Hence the cold chain is generally considered to start after the harvesting or processing of food products.
Figure 2. represents various steps of a typical mango export cold chain considered for simulation. After harvesting the mangoes are precooled to remove the field heat and bring it to an appropriate temperature for storage. It is then transferred via roadways to port for export. The cold chain finally concludes when the mangoes reach the consumer for domestic refrigeration (Ovca and Jevšnik 2009). The total cold chain duration may range from a few hours to several months depending upon the type of product and its destination. Each stage in the cold chain has a noteworthy impact on final overall quality of produce (Mercier et al. 2017).

3.3. CFD Model for Data Generation

Giving consideration to different stages of mango cold chain, three different CFD models are developed for each unit of operation, including precooling, road transport and sea transport. In all the stages cooling air is circulated throughout the container or storage house to remove the field heat after harvesting and maintain a low temperature surrounding. The detailed models of *'Kesar'* mangoes, packaging boxes, standard Euro pallets and the reefer container all are developed in ANSYS Design modeler 2021 R2 as shown in Figure 3. All the models are discretized in ANSYS meshing release 2021 R2 using tetrahedral cells. Fine meshing is applied to zones experiencing higher velocity.

Simulations are performed to obtain the velocity and temperature distribution. Navier Stokes equations are solved in steady state mode to obtain velocity distribution. The results obtained, are provided as an initial condition to the energy equations, which is solved in transient mode to obtain time varying temperature distribution (Wu, Cronjé, et al. 2018; Wu and Defraeye 2018). By transferring temperature history of individual fruits from one stage to next, for example from precooling to road transport stage, temperature history of individual fruits is extracted for the entire cold chain. This data is used to further evaluate the quality decay of fruits(Pattanaik et al. 2022). The initial, boundary conditions and other parameters used for simulation are demonstrated in Table 1, Table 2 and Table 3.

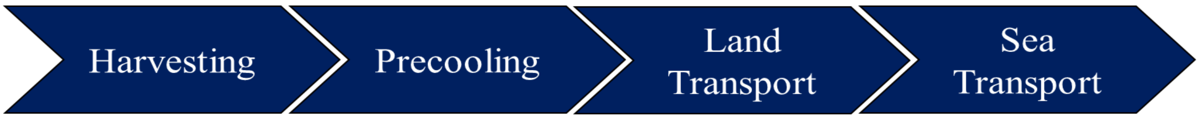


Figure 2. Mango cold chain(Pattanaik et al. 2022)

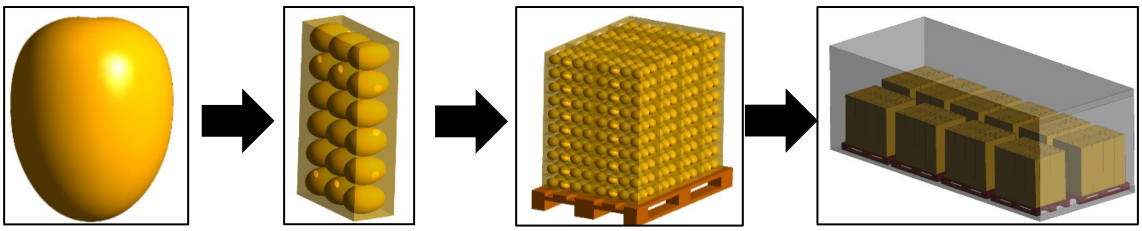


Figure 3. CFD models for different stages of cold chain (Pattanaik et al. 2022)

Table 1. Physical and Thermal properties (Han et al. 2017; Pattanaik and Jenamani 2020)

Parameters	**Value**
$\boldsymbol{\rho_{pulp}}$ (kg m^{-3})	710.305
$\boldsymbol{\rho_{seed}}$ (kg m^{-3})	960.01
$\boldsymbol{c_{p,pulp}}$ (J Kg^{-1} K^{-1})	3522.105
$\boldsymbol{c_{p,seed}}$(J Kg^{-1} K^{-1})	1875.98
$\boldsymbol{k_{pulp}}$(W m^{-1} K^{-1})	0.3345
$\boldsymbol{k_{seed}}$(W m^{-1} K^{-1})	0.1699
$\boldsymbol{\mu_a}$(kg m^{-1} s^{-1})	1.7722×10^{-5}
$\boldsymbol{C_{p,a}}$(J Kg^{-1} K^{-1})	1005.8
$\boldsymbol{k_a}$(W m^{-1} K^{-1})	0.02484
$\boldsymbol{\rho_a}$(kg m^{-3})	1.2474

3.4. Quality Degradation Calculation

The degradation in quality of perishable produce with respect to time can be quantified with the help of kinetic rate law model (Defraeye et al. 2019; Van Boekel 2008; Wu, Häller, et al. 2018). An overall quality attribute, denoted by parameter A, is given by

$$-\frac{dA}{dt} = kA^n$$

where t is time [s], k is the rate constant [s^{-1}], n is the order of reaction which determines change of $A$with respect to time.

By varying the value of n different quality degradation parameters, like lipid oxidation, enzymic degradation, vitamin loss, can be analyzed.
For n=0: $A = A_o - kt$
For n=1: $A = A_o e^{-kt}$
where A_o is quality at start of the cold chain. k is dependent on temperature, which is further solved over time with the help of Arrhenius relationship, given as:
$k = k_o e^{-\frac{E_a}{RT}}$
where k_o is a constant [d^{-1}], E_a is the activation energy [J mol^{-1}], R is the ideal gas constant [8.314 J mol^{-1}K^{-1}], T is the absolute temperature [K].

Table 2. Export conditions (Agriculture 2013)

Conditions	**Value**
Harvesting Temperature	308 K
Air circulation rate during precooling	1290 m^3/h
Cooling air temperature during precooling	286K
Air circulation rate during transport	5.5283m/s
Cooling air temperature during transport	283 K

Table 3. Variable heat of respiration (American Society of Heating Refrigerating and Air-Conditioning Engineers Inc. 2010)

Temperature (K)	**Heat of Respiration (W/m^3)**
10˚C	94.755
20˚C	158.144
25˚C	252.869

4. Results and Discussions

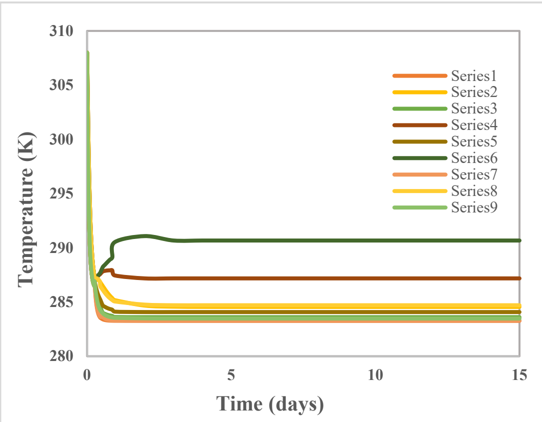
4.1. Thermal heterogeneity

The temperature distribution, of mangoes undergoing cold chain export process, at different locations inside the warehouse and reefer container are presented graphically in Figure 4a. Randomly nine points are taken from various locations, including top, bottom and centre, of the warehouse and reefer container to obtain the temperature distribution. The temperature data is extracted from the centre of mangoes as these are the last location to reach the desired temperature and hence represents the actual quality. The results show heterogeneous temperature distribution among the mangoes placed at different locations. The mangoes showing higher temperature are expected to have lover quality and hence shelf life.

4.2. Quality Evolution

The overall quality evolution of the above-mentioned nine points is evaluated by using the Kinetic rate law model. For the current study, only zeroth order reaction kinetics, which includes browning of surface, lipid oxidation and enzymatic degradation, is taken into account. Mangoes can be stored for 28 days at 285K (Kanade, Gajbhiye, & Salvi, 2017), which indicates that its initial overall quality attribute is 100 % and after 28 days it is 1 % that is it's in non-consumable condition. An increase in temperature of 10K decreases the shelf life of the fruit by a factor of 2 (Kanade et al., 2017). Other parameters, like k_o and E_a, are calculated from the equations mentioned in section 3.4 and these conditions.

The variation of quality attributes with respect to time is shown in Figure 4b. The decay in quality attributes reveals heterogeneous distribution. Mangoes at position 3,4,8 and 9 shows higher quality decay than others and hence will have less shelf life. This can be due to uneven airflow distribution. The locations where the cooling air-circulation is poor remains at higher temperature and displays lower quality.

a.


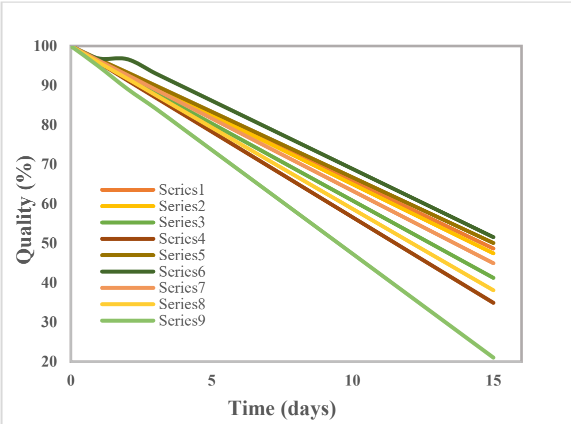
b.


Figure 4. a. Temperature variation with respect to time b. Overall quality variation with respect to time

4.3. Solution Implications

The proposed mathematical model is implemented for mango cold chain considering the quality decay in transit. As a case study of cold chain export is considered from India to Singapore, so the initially the source port, various destination locations in Singapore, their respective demands and the distance between source and destination cities, are determined as shown in Table 4.

Table 4. Location of source and destination cities

Source Port	Destination	Distance from source (km)	Demand
Jurong Port	Bedok	23.344	100
	Clementi	5.005	200
	Yishun	18.6435	300
	Choa Chu Kang	9.1243	100
	Serangoon	17.6521	500
	Geylang	18.5047	700
	Novena	13.7466	700
	Bishan	14.9976	100
	Sembawang	19.3016	300

	Outram	13.2193	100
	Seletar	20.849	200

The vehicle speeds and unit transportation cost are assumed to be constant for all the vehicles. The temperature and quality data are obtained from CFD simulation and Kinetic rate law model, respectively, as mentioned above. The minimum time of export from India to Singapore via seaways takes around 15 days, so the simulation is performed accordingly. The final quality data is calculated from extracted temperature taken (Figure 4) from the centre of mangoes at different locations inside the container is shown in Figure 4b.

Table 5. Final Assignment

	Bedok	Clementi	Yishun	Choa Chu Kang	Serangoon	Geylang	Novena	Bishan	Sembawang	Outram	Seletar
Quality-1	0	0	0	0	100	700	700	0	0	0	0
Quality-2	100	100	0	100	0	0	0	100	300	100	0
Quality-3	0	100	300	0	400	0	0	0	0	0	200

Based upon the simulated data obtained, the quality levels of mangoes inside the container at the destination can be divided into three segments – quality level 1, 2 and 3, which constitutes mangoes having an overall quality value above 45%, from 35-45% and below 35% respectively.
All these factors are incorporated into the mathematical model developed and solved, to obtain an optimal assignment of required quality mangoes to demand locations based upon the distance from source port as shown in Figure 5 and Table 5. All the algorithms developed are coded in python.

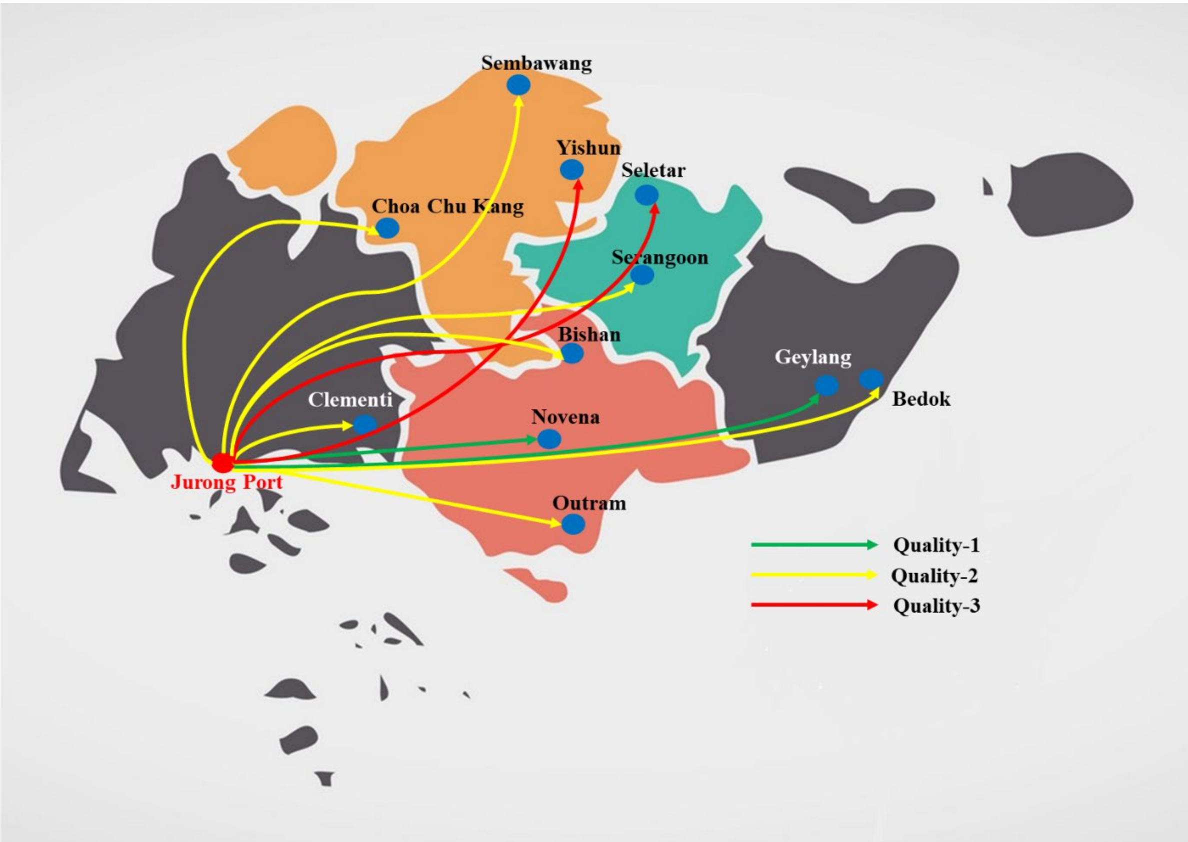


Figure 5. Singapore map showing distribution plan based upon quality of produce

5. Conclusion and Future Research

The growing concern about food quality and safety in the world market and its dependency on temperature, have led to challenging research on cold chain monitoring. Temperature needs to be continuously monitored to maintain the quality and increase the shelf life of the perishables. This study focusses on developing a comprehensive methodology for distribution planning for perishables by including its quality attributes decay along the cold chain. With the case of export of an Indian mango variety namely *'Kesar'*, from India to Singapore, CFD simulations are performed. Various stages of cold chain namely harvesting, precooling, road and sea transport are simulated in order to obtain the temperature-time history throughout the cold chain. With the help of Kinetic rate law model, an overall quality in terms of percentage is calculated. A mathematical model is successfully developed which aims to generate an optimized distribution plan by minimizing the total cost of transportation, including the quality degradation. However, certain real situation issues including traffic congestion, multiple perishables in one vehicle have not been incorporated into the model. For further research, a multi objective problem can be considered which can include maximization of quality as well as minimization of cost. The traffic congestion can also be added as a constraint to obtain more realistic scenario for effective routing.

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