



Research article

Production routing in perishable and quality degradable supply chains

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ABSTRACT

Generally, the major goal in perishable supply chains is preserving the product's quality along with improving its logistic performance. In this regard, temperature seems to be the most important and most sensitive factor, since uncontrolled temperature has shown to have great impact on reducing product quality. In this study, an integrated production routing model for a perishable product was developed; considering the production, inventory, storage temperature, routing and vehicle temperature. To solve the problem, a hybrid search algorithm combining the variable of neighborhood search algorithm and the mechanism of the simulated annealing algorithm was designed. In order to evaluate the validity of the proposed algorithm, its results were compared with that of the CPLEX solver in the GAMZ software environment. Comparison of the results of the two methods shows the efficiency of the proposed algorithm to solve this problem. As a case study, the proposed model was also applied in a real industrial case. According to the results, this company can greatly reduce its distribution and inventory costs and also avoid waste by using this program.

1. Introduction

The major goals of organizations are to minimize the production and distribution costs and improve on-time delivery while customers do not face any shortage. Moreover, determining the appropriate amount of production and inventory is also taken into consideration. Global competition has motivated partners in the food industry to follow a harmonious approach to have more productive supply chains. The primary intention of people is to buy safe and sound food, therefore, it is expected that the quality of goods are controlled and guaranteed over the supply and distribution chains (Schouten et al., 2012).

Typically, food degradation depends on the indigenous and exogenous characteristics of foods involved in all stages of the network and the length of time in which foods are subjected to these parameters. Therefore, in Food Supply Chain Networks (FSCNs) products need to be kept in a temperature-controlled environment.

Much attention has been given to food quality decay modeling and the development of Time Temperature Indicators (TTI). In this study, the Gompertz equation was employed to estimate products quality decay. This equation will be explained more in section 6-1.

Production routing problem (PRP) connects two problems, namely the inventory routing problem (IRP) and the lot-sizing problem (LSP), to optimize production, inventory, distribution and

routing decisions. The lot-sizing problem and the inventory routing problem have ignored a significant feature of the supply chain operational planning process. The lot-sizing problem, when considering direct shipment, does not make decision about routing, and the inventory routing problem does not consider the production part. Production routing problem is an integrated operational planning problem jointly optimizing production, inventory and routing decisions, simultaneously.

The total cost-benefit achieved by coordinating production and distribution planning ranged from 3% to 20% (Agnetis et al., 2014). The integration and optimization of several activities within the food supply chain does not only reduce the chain cost, but also provides better food quality management. Therefore, production routing problem with regard to the products quality, improves the performance of food supply chain networks.

The structure of this paper is as follows: In the next section (Section 2), a review of previous studies is presented. Section 3 deals with multi-product routing problem considering deterioration of product quality along with model formulation. In Section 4, solution methods are described. A case study discussion dealing with a chicken supply chain and the application of the proposed approach will be shown in Section 5, followed by the conclusions in Section 6.

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2. Literature review

Various studies have been conducted on the supply chain of perishable products. Rong et al. (2011) presented a methodology to model food quality degradation in such a way that it could be integrated into a mixed-integer linear programming model applicable for production and distribution planning. The method was based on the time-temperature profile during storage and transportation of the product and was linked to decision-making on the temperatures during storage and distribution. The resulting model was applied in an illustrative case study. Zhang and Chen (2014) addressed a vehicle scheduling problem in the cold chain logistics of the frozen food delivery industry. They proposed a model that managed the delivery of a variety of products. The aim of this model was to find the optimum routes by which delivery costs were minimized. They then proposed a genetic algorithm for the solution model. Jia et al. (2014) presented a two-echelon supply chain mixed-integer programming model under discrete time. The aim of this model was to optimize inventory and routing decisions. In the objective function they considered loading cost. They also set a soft time window during the transportation stage and a hard time window during the sales stage because the product was perishable. They developed a two-phase algorithm. In the first phase, they used a tabu search algorithm to obtain the retailers' ordering matrix and the in the second phase, adopted a saving algorithm and a neighborhood search to generate production scheduling and distribution routing. Shaabani and Kamalabadi (2016) presented a problem involving a multi-period and multi-perishable product in two-level supply chains. The objective function was to minimize the total cost while ensuring that no stock-out occurs. To solve the model, they proposed a population-based simulated annealing algorithm. Devapriya et al. (2017) developed a mixed-integer programming model for a perishable product that must be produced and distributed before it becomes unusable. The objective function was to minimize the total cost. This model is making decisions about fleet size and the trucks' routes subject to a planning horizon constraint. They proposed a heuristic method based on evolutionary algorithms to solve the models. Hiassat et al. (2017) presented a location-inventory routing model for perishable products. They developed a genetic algorithm approach to solve the problem efficiently. The result shows that this approach achieves high quality near optimal solutions in reasonable time.

Given the increasing focus on the quality of food materials in the world market and the impact of temperature on the quality of food, this issue is a challenging research which needs to be focused on seriously. Therefore, if food quality degradation model is combined with production and distribution model, new opportunities will be created for improving the performance of food chain networks.

In the field of logistics of perishable products, a few researchers specifically consider temperature during distribution. Most of these studies have considered direct distribution and have paid no attention to vehicle routing problems with optimum temperatures. In this research, we present a production routing problem with regard to products' quality.

3. Modeling production routing problem along with considering Product's quality

Food is a perishable product that has a relatively short lifetime and begins to deteriorate after production. For the safety and quality of food, the temperature needs to be constantly monitored and controlled along the supply chain. This includes monitoring the duration of storage, transportation, and generally the production-to-delivery time to the final consumer. Therefore, coordination among production, distribution and inventory systems is necessary which can be realized by integrating chain planning.

In this section a mixed-integer linear programming model for production routing problem considering products' quality and optimum temperature is developed. $G = (N, A)$ is a complete directed graph where

N represents the plant and the customers (nodes) and A is the set of arcs connecting the nodes; where $A = \{(i, j): i, j \in N, i \neq j\}$. The plant and the customers are represented by node 0 and $i \in \{1, 2, \dots, N\}$, respectively.

The limit of time includes a set of time periods $t = \{1, \dots, T\}$. Multi-product can be prepared at the plant and distributed by a same fleet of limited capacity vehicles $k = \{1, \dots, K\}$. Each retailer's demand for each product is constant in each period. It is assumed that the products produced at the plant are at the highest level of quality and their quality is not decreased until loading time. Product quality depends on time and temperature. The capacity of plant and retailers' warehouse is limited and known. The temperature of the warehouse and vehicles in each period is constant. The goal of this problem is to determine the production lot-size for each period, the amount of products sent to each retailer and how to distribute products in a way that constraints on production, distribution, inventory and quality are met.

3.1. Relative cooling cost

The cost of storing along with transporting goods in a temperature-controlled distribution chain is dependent on the surrounding temperature. To determine these costs, the thermal characteristics of the cooling processes must be taken into account. Without taking energy loss into account, the coefficient of performance (COP) for refrigeration is obtained as (Whitman and Johnson, 2012):

$$COP = \frac{Q_L}{W} = \frac{T_L}{T_H - T_L} \quad (1)$$

Where Q_L is regarded as the heat conveyed from a lower level of temperature to a higher one, W is the input energy, T_L and T_H are the lower and higher temperatures measured in Kelvin, respectively. For example, if $T_H = 298$ K (25 °C), and $T_L = 273$ K (0 °C), then $COP = 10.92$. This means that for each unit consumption of energy, the cooling system can absorb up to 10.92 units of heat from the refrigerator. Eq. (1) also states that more energy is needed for lower temperatures. Assuming that the cost of each unit of energy is constant, the total energy cost should be proportional to the amounts of energy consumed. To obtain the relative cost of different temperature, Eq. (1) is used. Assuming that the electrical energy unit cost is 1 at 0 °C, the relative cost at higher temperatures can be obtained by multiplying the coefficient of COP values by the unit cost (where an environment temperature T_H of 25 °C = 298 K is considered). For instance, using the Eq. (1), COP at 2 °C (10.92), and its relation to the COP at 4 °C (277 K/(298 K-277 K) = 13.19), we get a cost ratio of 10.92/13.19 = 0.827. The results for all temperature levels are shown in Table 1.

By multiplying the relative costs rc_k presented in Table 1 by the relevant transportation cost parameter of arc (i, j) , the cost parameters for different temperatures are obtained, i.e. $c_{ijte} = dis_{ij} * rc_k$.

The notations used in the mathematical model are presented in the Appendix.

3.2. Assumptions

The following assumptions are used:
Assumptions:

- There is a two-schelon supply chain including one manufacturer and numerous retailers.
- Production facility (factory) produces various products and production capacity is limited in each period.
- This study considers a multi-product problem with deterministic demand.
- In each period, routing is started by moving vehicles from the plant to the retailer and the vehicle returns back to the plant at the end of the service.

- Split deliveries are not permitted.
- Products are perishable and their degradation rate depends on storage time and environmental conditions.
- The manufacturer and retailers can store the products.
- The storage capacity of both the manufacturer and retailers is limited and no shortage is allowed.
- It is possible that some products are not produced and retailers are not visited in each period.
- Vehicles are homogeneous and their capacities are limited.
- At the beginning of the route the temperature of each vehicle is set and remains constant until the end of the route.
- The temperature of the manufacturer's and retailers' warehouse is adjustable and is fixed in each period.
- In the manufacturing warehouse, quality is fixed. Also, product quality from production to loading is fixed.

3.3. Mathematical model

The model formulation of the problem is as follows:

$$\min \sum_t S C_t * O_t + \sum_n V_n * p_{t,n} + \sum_k \sum_t f * y_{k,t} + \sum_i \sum_j \sum_k \sum_t \sum_{te} C_{i,j,te} * x_{i,j,k,t,te} + \sum_i \sum_t \sum_{te} h_{i,te,n} * I_{i,t,te,n} + \sum_i \sum_t \sum_{te} g_{i,te} * e_{i,t,te} \tag{2}$$

Subject to:

$$\sum_{te} I_{i,t-1,te,n} + p_{t,n} = \sum_i q_{i,t,n} + \sum_{te} I_{i,t,te,n} \quad \forall t \in T, n \in N_p \tag{3}$$

$$\sum_{te} I_{i,t-1,te,n} + q_{i,t,n} = d_{i,t,n} + \sum_{te} I_{i,t,te,n} \quad \forall i \in N_C, t \in T, n \in N_p \tag{4}$$

$$\sum_{te} \sum_n I_{i,t,te,n} \leq l_0 \quad \forall t \in T \tag{5}$$

$$\sum_{te} \sum_n I_{i,t-1,te,n} + \sum_n q_{i,t,n} \leq l_i \quad \forall i \in N_C, t \in T \tag{6}$$

$$\sum_n I_{i,t,te,n} \leq M * e_{i,t,te} \quad \forall i \in N, t \in T, te \in TE \tag{7}$$

$$\sum_{te} e_{i,t,te} \leq 1 \quad \forall i \in N, t \in T \tag{8}$$

$$p_{t,n} \leq o_t * M 1_{t,n} \quad \forall t \in T, n \in N_p \tag{9}$$

$$\sum_n q_{j,t,n} \leq l_j * y_{j,t} \quad \forall j \in N_C, t \in T \tag{10}$$

$$\sum_i \sum_k \sum_{te} x_{i,j,k,t,te} = y_{j,t} \quad \forall j \in N_C, t \in T \tag{11}$$

$$x_{i,i,k,t,te} = 0 \quad \forall i \in N, k \in K, t \in T, te \in TE \tag{12}$$

$$\sum_{j \in N_C} \sum_{te} x_{i,j,k,t,te} \leq y_{k,t} \quad \forall k \in K, t \in T \tag{13}$$

$$\sum_{i \neq j} x_{i,j,k,t,te} = \sum_{i \neq j} x_{j,i,k,t,te} \quad \forall j \in N, k \in K, t \in T, te \in TE \tag{14}$$

$$\sum_k \sum_t u_{1,k,t} = 0 \tag{15}$$

$$u_{i,k,t} + 1 \leq u_{j,k,t} + M * (1 - x_{i,j,k,t,te}) \quad \forall i \in N, j \in N_C, k \in K, t \in T, te \in TE \tag{16}$$

$$\sum_{j \in N_C} \sum_n \left(q_{j,t,n} * \left(\sum_i \sum_{te} x_{i,j,k,t,te} \right) \right) \leq cap \quad \forall k \in K, t \in T \tag{17}$$

$$q s_{1,t,n} = q_{0,n} \quad \forall t \in T, n \in N_p \tag{18}$$

$$q s_{i,t,n} = \sum_j \sum_{te} \sum_k q s_{j,t,n} * x_{j,i,k,t,te} + \sum_j \sum_{te} \sum_k \Delta q 2_{j,i,te,n} * x_{j,i,k,t,te} \tag{19}$$

$$\forall i \in N_C, t \in T, n \in N_p$$

$$q_{i,t,n} \geq w_{i,t,n} \quad \forall i \in N, t \in T, n \in N_p \tag{20}$$

$$q_{i,t,n} \leq M * w_{i,t,n} \quad \forall i \in N, t \in T, n \in N_p \tag{21}$$

$$Cmax_n - q s_{i,t,n} \geq w_{i,t,n} * (Cmax_n - qmax_{i,n}) \quad \forall i \in N, t \in T, n \in N_p \tag{22}$$

$$\sum_{t=1}^{t'} TQ_{int'} = d_{int'} \quad \forall i \in N, t' \in T, n \in N_p \tag{23}$$

$$q_{i,n,t} = \sum_{t'=t}^T TQ_{i,n,t,t'} \quad \forall i \in N, t \in T, n \in N_p \tag{24}$$

$$TQ_{i,n,t,t'} \leq M * z_{i,n,t,t'} \quad \forall i \in N, t \in T, t' \in T, n \in N_p \tag{25}$$

$$q s_{i,t,n} + (t' - t) * \Delta q 1_{ie,n} * e_{i,t'-1,te} * z_{i,n,t,t'} \leq cmax_n \quad \forall i \in N, t \in T, n \in N_p, t' \in T, te \in TE \tag{26}$$

The objective function (2) minimizes the total cost which includes production setup cost, production variable cost, fixed costs for each vehicle, routing cost, inventory holding costs for the manufacturer and retailers and inventory holding fixed cost for the manufacturer and retailers. The inventory flow balance equations for manufacturer and retailers are guaranteed by relations (3) and (4), respectively. Constraints (5) and (6) are storage capacity of manufacturer and retailers, respectively. Constraint (7) indicates products can be stored in plants or the retailers' warehouse if the warehouse is used during that period. Each facility can only operate at one temperature level. Hence, constraint (8) implies that one temperature level has to be chosen for each storage facility. Relation (9) is production capacity constraint. Constraints (10) to (16) are the vehicle loading and routing restrictions. Constraint (10)

Table 1. The relative cost between different temperatures using 0 °C as reference.

Temperature (°C)	0	2	4	6	8	10	15
cop ¹	10.92	11.95	13.19	14.68	16.52	18.8	28.8
rc _k ²	1	0.913	0.827	0.743	0.661	0.58	0.37

¹ Coefficient of performance.
² Relative transportation costs.

allows delivery quantity to be positive if customer i is visited in period t and can only be visited by one vehicle (11). Constraint (12) ensures that a retailer does not visit itself. Constraint (13) ensures that each specific vehicle from the plant can go to the retailers, if the vehicle is used during that period. Route continuity is enforced by constraint (14). Constraints (15) and (16) are sub tour elimination constraints. Constraint (17) indicates vehicle capacity constraint. Constraint (18) is the microbial count of product n in the plant. Constraint (19) shows the microbial count of product n while it reaches retailer i . Constraints (20) and (21) ensure that if retailer i is visited in period t , then this retailer receives product n . Constraint (22) indicates that the microbial count of product n while reaching retailer i will be less than the maximum acceptable microbial count. Constraint (23) ensures that the amount of product n delivered to retailer i from period 1 to period t and is consumed in period t' is equal to demand for period t' . Constraint (24) ensures that the amount of product n which is delivered to retailer i in period t is equal to the sum of the amount of product n delivered to the retailer i in period t and consumed from the period t to the last period. Constraint (25) ensures that the amount of product n delivered in period t which is consumed by retailer i in period t' , takes a positive value. Constraint (26) ensures the inventory quality.

The proposed production routing problem can be easily reduced to vehicle routing problem (VRP) with some restrictions. Since VRP is classified as an NP-hard problem (Kumar and Panneerselvam (2014)), the proposed model is also NP-hard. Given this, solving for optimality is not an option for problems of large size, and therefore heuristic algorithms must be developed to find good solutions.

4. Solution methods

The proposed model is a nonlinear mixed-integer model that was first linearized, and then used by CPLEX solver in the GAMS software environment to solve small size problems; and to solve the model in large sizes, a hybrid algorithm that combines the variable neighborhood search algorithm (VNS) and simulation annealing algorithm was developed.

4.1. Solution representation

The solution representation is a matrix in which the number of rows represents the total number of retailers and the number of columns represents the number of horizons. The matrix of the answer consists of binary numbers. In the solution matrix, if a cell gets one or zero, it means this retailer is visited or not visited, respectively, in this period. Figure 1 illustrates the solution matrix for four retailers and three periods.

4.2. Initial solution

The meta-heuristic algorithm begins with an initial solution that is obtained by the heuristic algorithm. Four steps were taken to generate the initial solution. In the first step, retailers to be visited in all periods were selected. In the second, the inventory and its costs were checked for retailers, if the cost was better, then the retailers hold inventory instead of visit. In the third step, the temperature of vehicles and the warehouse of retailers were monitored to ensure that they provide the required quality level and the minimum cost. In the fourth step, production planning is done and solved by the exact software.

4.3. The proposed algorithm

After finding the initial solution, the VNS algorithm finds the neighborhood of the current solution according to the prioritization of the neighborhood structures. Then, the algorithm tries to improve the solution with local search. If the cost is improved, this answer is accepted. To avoid falling into the optimal local, if the cost is not improved, it is accepted with probability P and the neighborhood search continues until it reaches the specified maximum repetition, then enters the second

neighborhood structure. The algorithm continues until a maximum number of iterations is achieved.

The variable neighborhood search algorithm consists of two phases; the neighborhood structure phase and the local search phase.

4.3.1. Neighborhood structure

The purpose of this phase is to create a sudden change in solution. In this study, a set of twelve neighborhood structures were used. Neighborhood structures are sorted from the most simple neighborhood structure to the most complex one according to their variation effects on the solution. Two kinds of neighborhood structure; inventory neighborhood structure and route neighborhood structure were considered.

4.3.2. Local search phase

After each neighborhood structure, the algorithm uses the local search to improve the solution. The local search should be done on the output of the neighborhood structure. When neighborhood structure achieves a service program for a number of retailers in the horizon, then a local search tries to create a better program for those retailers. If this program is better than the previous one, the new solution will be accepted. The proposed local search is 2-opt and swpt, one of which is randomly selected at each stage.

4.4. Sample problem

To evaluate the performance of the designed algorithm, 18 problems were randomly generated. In these samples, the number of periods were 2–7, the number of retailers were 2–5, the number of products were 2 and 3, and as for the temperature, levels 2 to 4 were considered.

5. Computational Results

The samples' problems in different dimensions were solved by the proposed meta-heuristic algorithm. The model was implemented in GAMS 24 and MATLAB 2016-b software. The test runs were performed on a Core i5 computer with a 2.4 GHz processing unit and 16 GB of memory.

To evaluate the efficiency of the algorithm, its results were compared with the results of CPLEX solver in the GAMS software environment. Table 2 shows the results of the exact solution and the proposed algorithm for 17 samples. In the second column, the sample size is written as $T-NC-N-TE$, where it denotes the number of periods, the number of retailers, the number of products, and the number of temperature levels, respectively. The objective value and run time of GAMS solver were inserted in the third and fourth column, the objective value and run time of proposed algorithm were inserted in the fifth and sixth column, and the gap is expressed as a percentage in the last column that denotes the difference between the objective value of the proposed algorithm and that of GAMS solver.

1	0	1
1	0	0
1	1	0
1	0	1

Figure 1. Solution matrix for 4 customers and 3 periods.

Table 2. Computational results of propose algorithm and GAMS for the test problems.

Number	Class	GAMS		Propose algorithm		Gap%
		Objective value	Time(s)	Objective value	Time(s)	
1	2-2-2-2	1128.91	0.47	1128.91	72	0
2	3-2-2-2	1697	0.48	1697	84	0
3	7-2-3-2	5333.18	0.77	5333.18	92	0
4	6-2-2-3	3338.39	7	3338.39	85	0
5	2-3-3-2	2170.27	3	2170.27	86	0
6	3-3-3-2	2479.9	33	2797.61	88	0.7
7	2-4-3-2	2745.92	37	2822	202	2.7
8	3-3-3-2	3484.94	108	3538.62	180	1.5
9	3-3-2-3	2409.27	233	2409.27	190	0
10	4-3-3-2	4412.95	264	4412.95	151	0
11	2-5-2-2	2715.33	748	2720.22	119	0.18
12	3-4-2-2	3282.33	14220	3286.88	173	0.13
13	6-3-2-2	5043.32	9963	5063.17	221	0.39
14	3-4-3-2	4260.88	10800	4336.96	176	1.7
15	6-3-3-	6517.27	28440	6579.64	195	0.95
16	5-3-3-3	5352.65	54920	5384.9	148	0.6
17	4-5-2-4	5170.72	>57600	5197	442	0.5

Comparison of the results of the meta-heuristic algorithm and the exact solution shows that the average gap of the proposed algorithm is 0.52% and the average and the solution time for the algorithm is much less than that of the exact solution which indicates the efficiency of the proposed algorithm.

6. Case study

The proposed model was implemented in a chicken packing plant in Isfahan, Iran. This company daily supplies chicken from an aviculture with a veterinary license and after the chicken is segmented, it is packed in dishes, and is then sent to customers by a refrigerated vehicle. The company's production capacity is ten tons per day. The products are warm complete chicken, thigh, chest, shoulders and wings, which are packed in 2-kg packages. The unit packing cost is 4000 Rials and the other costs include water, electricity, etc., which is estimated to be 10166670 Rials per day.

The company has a cold room with a capacity of 2 tons for storage. The fixed cost of the cold room is 833330 Rials and the storage cost is 13 Rials per Kg per day. It should be noted that storage costs have been calculated at 0 °C, which is multiplied by rc_k coefficient according to the cold room temperature. The company has six refrigerated vehicles with a capacity of 2 tons. Products are shipped to customers daily by these vehicles. Depending on the total demand, a number of vehicles are used. The fixed cost of each vehicle is 533330 Rials and its travel cost is 750 Rials per Km.

The customers are restaurants, chicken supermarkets, stores and hypermarkets. A field survey was conducted for 5 days in order to understand the customers' demand for various goods. The daily storage cost for each customer is estimated to be at 30000 Rials. The temperature was set at 4 levels, 0°, 4°, 8°, and 15 °C for vehicles and the customer warehouse. Here the model should obtain the optimum temperature due to product sensitivity and cost.

6.1. Quality degradation model

In this study, the Gompertz equation was employed to estimate microbial growth. In a study by Ghollasi-Mood et al. (2017) the microbial growth curve was estimated by fitting the data with the Gompertz equation.

$$\log N_{(t)} = \log N_0 + A * \exp \left\{ - \exp \left\{ \left[(\mu_{\max} * 2.7182) * \frac{LPD - t}{A} \right] + 1 \right\} \right\} \quad (27)$$

Where, $N_{(t)}$ and N_0 represent the microbial count at time t and $t = 0$, respectively. A is the increase in microbial count between time 0 and the maximum population density achieved at the stationary phase, μ_{\max} is the maximal growth rate, LPD is defined as the lag phase duration (days) and t is the storage time (days). In order to identify the thermal sensitivity of microorganisms during storage, the effects of temperature on LPD and the microbial growth rate were estimated using the Arrhenius function. The adaptation rate of microorganisms is shown as the reciprocal of lag phase ($1/LPD$) was fitted by the below relation.

$$\frac{1}{LPD} = Z \exp(-E_{LPD} / RT) \quad (28)$$

Where Z is the pre-exponential factor (days^{-1}), T the absolute temperature, E_{LPD} the activation energy (kJ/mol) and R the gas constant (8.31 J/K* mol).

The bacterial growth rate is affected by temperature(T) and is shown as below:

$$\mu = A' \exp(-E_{\mu} / RT) \quad (29)$$

Where μ , A' , T , E_{LPD} and R are the specific rate of growth, the pre-exponential factor, the absolute temperature, the activation energy (kJ/mol) and the gas constant (8.31 J/K* mol), respectively.

By definition, A is calculated as follows:

$$A = C_{\max_n} - C_{0_n} \quad (30)$$

Where C_{\max_n} is the maximum microbial count allowed in healthy products and C_{0_n} is the initial amount of microbial level in the product. The microbial level of the product is measured at 4 temperature levels of 0°, 4°, 8°, and 15 °C.

To obtain the growth curve, first, the μ and LPD curve were calculated based on the temperature variations, then this value was placed in Eq. (27) and the curve of $\log N_{(t)}$ was obtained. Now, it was possible to measure microbial growth for all levels of temperature at different times. The maximum microbial count in healthy chicken is 10^8 . When microbial count in chicken meat reaches this number, the product becomes spoiled and unusable.

Table 3. Production amount of each product per period.

Period	Complete chicken	Shoulder and wing	Chest	Thigh
1	413	234	1006	881
2	425	243	1044	915
3	481	273	1171	1020
4	756	449	1873	1641
5	617	361	1504	1316

Table 4. The visit schedule of trucks in period 1.

Truck1	plant	19	18	20	22	21	24	23	plant									
Truck2	plant	1	8	7	25	17	31	15	35	34	12	32	2	3	plant			
Truck3	plant	27	26	9	11	10	28	16	36	30	29	14	33	13	4	5	6	plant

6.2. Computational results

After matching the data with the problem, the problem was solved by the proposed algorithm. For running the algorithm, Matlab software was used. The algorithm was run 10 times and the best answer was chosen.

The total cost including the cost of production, maintenance and transportation for 5 periods was calculated to be 128959370 Rials. The optimal amount of production in each period of each product is given in Table 3.

By solving the model, the optimal routes for each vehicle in each period were obtained. The optimal routes for the first period is given in Table 4. Each truck leaves the plant and after delivering the products to the customers will return back to the plant. The results also showed that the optimum temperature of all vehicles is 15 °C.

The results also indicated that no inventory is held in the plant, that means the production quantity in each period is equal to the total demand of customers during that same period. Therefore, the inventory holding cost in the plant is zero and the production cost is 117373350 Rials. The optimal inventory for customers is shown in Table 5. The absence of a customer number in Table 5 for any period indicates that the customer does not hold inventory at that period.

For example in the first period, customer 22 receives as much demand as the first and second periods and stores the demand of the second period at 8 °C, so customer 22 is not visited in the second period. In the second period, customer 24 receives the products for the second and third periods and maintains the demand of the third period in a warehouse with a temperature of 8 °C. Customer 34 receives demands for the second, third and fourth periods, and keeps inventory of products of the third and fourth periods in the second period at 4 °C.

7. Discussion and conclusions

Given the increasing focus on the quality of perishable items in the world market and the impact of temperature on their quality, this issue has been a challenging research which needs to be focused on seriously. For the safety and quality of food, the temperature needs to be constantly monitored and controlled along the supply chain.

A few researchers have specifically considered temperature during distribution. Most of these studies have addressed direct distribution from manufacturer to customer and have not paid attention to delivering goods to a set of customers. In this study, due to the necessity of coordination between production, distribution and inventory systems, we addressed a routing problem and a mixed-integer linear programming model for production routing problem considering products' quality and optimum temperature.

It was assumed that the products produced at the plant were at the highest level of quality and their quality did not decrease until loading time. The capacity of the plant and the retailers' warehouse was limited and known. The temperature of each vehicle in each period along with that of the plant and retailers' warehouse was set at the beginning of the route and remained constant until the end of the route.

As the proposed production routing model was NP-hard, the exact solution can be used to solve the model with a small-size problem. To solve the model, a meta-heuristic algorithm was developed. 18 problems were generated, randomly. Comparison of the results of meta-heuristic algorithm and the exact solution showed the efficiency of the proposed algorithm.

In this research, the proposed model was implemented in a chicken packing plant in Isfahan. This company daily receives chicken from an aviculture and after segmentation and packing, the chicken is sent to customers (restaurants, chicken supermarkets, stores, and hypermarkets)

Table 5. Customers inventory amount of each product in periods.

period	customer	complete chicken	shoulder and wing	chest	thigh
1	22	6	3	15	13
2	24	14	8	34	34
	34	15	11	37	33
3	25	18	10	44	38
	34	10	8	25	22
4	14	23	14	56	49
	20	19	11	47	41
	21	18	10	44	38
	22	13	7	31	27
	24	17	10	40	35
	27	26	15	63	55
	35	19	11	47	41

by a refrigerated vehicle. The temperature was set at 4 levels, 0°, 4°, 8°, and 15 °C for vehicles and the customer warehouse; in which the model should find the appropriate temperature.

By solving the model, the production lot size, products inventory and optimal routes for each vehicle in each period were obtained. The total cost including the production, maintenance and transportation costs for 5 periods was calculated to be 128959370 Rials. By applying this plan the company will have saved 14268500 Rials, monthly. The results also indicated that the production quantity in each period is equal to the total number of demands in that period. It means no inventory will be held in the plant. Further, the sensitivity analysis on the dimensions of the problem revealed that as the unit cost of maintenance increases (up to 30%), maintenance costs also increase, but if the cost increases by more than 30 percent, it is no longer reasonable to hold inventory. The sensitivity analysis also showed that the suitable temperatures for vehicles are 15 °C and optimum warehouse temperatures are 4° and 8 °C.

Based on model performance results, it can be said that the model is a comprehensive program that can help supply chain management in determining production quantity, inventory, appropriate chain temperature and optimal vehicle routing with the lowest cost and a high product quality. In general, it can be concluded that if a factory can convince its customers to place their orders a few days earlier, the company can greatly reduce its distribution and inventory costs and also avoid waste by using this program.

There are good areas for further research. In the proposed model, packaging can be considered as a decision variable, and according to customer demand quality and cost optimization, decisions can be made

on product packaging. In some perishable chains, due to better performance and chain agility, it is sensible to consider a crossdocking system that was not considered in this research. In order to maximize the quality of the products in the chain, a multi-objective model can be developed to minimize costs and maximize quality.

Declarations

Author contribution statement

Fateme Manouchehri, Ali Shahandeh Nookabadi & Mahdi Kadivar: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Additional information

No additional information is available for this paper.

Appendix

Indices

i, j	Indices for manufacturer or retailers, where 0 relates to the manufacturer ($i, j \in \{0, 1, 2, \dots, N\}$)
k	Vehicle Index of ($k \in \{1, 2, \dots, K\}$)
t, t'	Planning period Index ($t, t' \in \{1, 2, \dots, T\}$)
n	Product Index ($n \in \{1, 2, \dots, N_p\}$)
te	Temperature level Index ($te \in \{1, 2, \dots, TE\}$)

Parameters

N	Number of retailers
K	Number of vehicles
T	Number of planning periods
N_p	Number of products
TE	Number of temperature levels
$C_{i,j,te}$	Cost of product transportation between node i and j at temperature level te
$h_{i,te,n}$	Storage cost of each unit of product n at manufacturer or retailer i at temperature level te
V_n	Cost for producing one unit of product n
f	The fixed cost of using a vehicle in each period
SC_t	Production setup cost in period t
$g_{i,te}$	Cost of maintaining the product over a specified period in retailer's warehouse i at the temperature te
d_{itn}	The demand for product n by retailer i in period t
c_p	Production capacity for each kind of product in each period
l_0	Inventory capacity of manufacturer
l_i	Inventory capacity of retailer i
Cap	Capacity of vehicles
M	A large positive value
$\Delta q_{te,n}$	The increase in the number of microbial for product n stored in retailer's warehouse for one period at temperature level te

(continued on next column)

(continued)

$\Delta q_{2i,j,t,n}$	The increase in the number of microbial for product n transported on arc (i,j) at temperature level te
$q_{0,n}$	Initial microbial count of product n
$qmax_{i,n}$	Maximum acceptable microbial count at the reaching time to retailers
$Cmax_n$	Maximum microbial count allowed for healthy product

The maximum production of each product in each period is shown by $MI_{t,n}$ obtained as follows:

$$MI_{t,n} = \min \left(C_p, \sum_{i' \geq t} \sum_{i \in N_C} d_{i',t,n} \right) \quad \forall n \in N_P, \forall t \in T$$

Decision variables

$P_{t,n}$	Production quantity of product n in period t
$I_{i,t,te,n}$	The n_{th} product inventory level at manufacturer or retailer i at the end of period t at temperature level te
$q_{i,t,n}$	Delivery quantity of product n to retailer i in period t
$u_{i,k,t}$	A positive variable for the sub tour elimination constraint that can be defined as the start time.
$x_{ijk,t,te}$	1 if vehicle k travels directly from node i to node j in period t at temperature level te ; 0 otherwise
$y_{j,t}$	1 if retailer j is visited in period t ; 0 otherwise
γ_{kt}	1 if vehicle k is used in period t ; 0 otherwise
$e_{i,t,te}$	1 if inventory stored in node i in period t at temperature level te ; 0 otherwise
o_t	1 if production takes pace at the plant in period t ; 0 otherwise
qs_{in}	Microbial count in product n at node i at the end of period t
w_{in}	1 if $q_{i,t,n}$ is positive; 0 otherwise
$TQ_{i,n,t,t'}$	The amount of delivered product n to retailer i in period t which is consumed in period t'
$z_{i,n,t,t'}$	1 if delivered quantity of product n to retailer i in period t which is consumed in period t' is positive; 0 otherwise

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