

Research Article

Integrated Quality-Based Production-Distribution Planning in Two-Echelon Supply Chains

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The integrated production-distribution (P-D) planning has turned into one of the most essential areas in supply chain (SC) management in recent years, especially in the case of perishable products in which the quality of products can change over time. Nonetheless, so far, the suggested models have focused on the P-D stages of the chain while the delivery of high-quality products to customers is of paramount significance in the perishable SC. In the present paper, a multiobjective, mixed-integer, and nonlinear programming (MOMINLP) mathematical model was developed for integrated P-D deteriorating items in a two-echelon SC that emphasizes quality degradation. Quality is monitored and calculated as a function of temperature and time throughout the SC, and the main purpose of the model is to first increase the quality of products delivered to customers and, second, minimize the SC costs. To optimize the problem, the particle swarm optimization (PSO) approach was also incorporated into the model. The obtained model was applied to a case study in Protein Gostar Sina Company in Iran, which resulted in decreased P-D costs as well as increased customer satisfaction.

1. Introduction

Supply chain (SC) can be depicted as a chain attempting to establish effective communication between customers and suppliers by efficient management of the flow of material, information, and money [1]. SCs include procedures that create certain values offered to the final customer as products or services. SC is a complicated system requiring its members to share their information to increase the integration of chain members, better coordinate financial flows and materials, and reduce the undesirable consequences of the SC [2]. Two essential areas in SC are production planning and distribution planning, while integration has also been significantly emphasized in this respect over the past years [3]. Nowadays, in markets worldwide, products with short life cycles as well as customers with great expectations make companies pay special attention to SC. Nevertheless, SC members require proper arrangement as well as harmonization to make a supply chain management (SCM) effective [4]. This can have serious implications for perishability that can in turn influence all SC processes such

as production process, inventory management, and distribution [5].

Recently, the integrated P-D planning models for deteriorating items have attracted considerable interest among researchers. This is especially the case for food SCs and real-world models that relate to product lifespans and efforts to deliver quality goods to customers. A range of topics is always discussed concerning the food SC. Food SCs are intricate and constantly changing. The effective network design for SC can significantly contribute to the flow of products, the reduction of the costs related to its transportation, and the increasing food safety [6]. Most studies in this area have attempted to model the issue of quality and decrease of product life in SC separately just using one of the models of production, distribution, or inventory. However, today the integration and presentation of models for simultaneous coverage of a broader segment of the SCs have found widespread popularity.

Considering the importance of an integrated model for simultaneous quality concern of products and P-D planning, the main purpose of the present paper is to provide a

multiobjective mathematical model for the integrated P-D problem of perishable goods which first maximizes the quality of products delivered to customers and second reduces the overall costs of the SC. To this end, in the current study, a multiobjective, mixed-integer, and nonlinear programming (MOMINLP) mathematical model was developed where the global criterion method (GCM) has been used for the allocation of weights to each objective function. In the proposed model, the perishability of goods in all stages of the SC (from production to delivery to the customer) is accurately measured based on the effective parameters of temperature and time where quality is defined as a function of temperature and time based on Arrhenius equation. Since by adding the Arrhenius equation, the mathematical model became nonlinear, and the Taylor series was used to linearize the model. Moreover, since one of the disadvantages of integrated models is the inefficiency of precise solution methods, the particle swarm optimization (PSO) meta-heuristic solution method was applied to enhance the efficiency of the proposed model and solve problems on large scales.

In addition to the above, since mathematical models are generally far from the real world, two steps were taken to bring the model closer to the real world. First, products were qualitatively graded according to the realistic customer demands. Second, to measure the real-world performance of the model, it was implemented in the poultry industry in Protein Gostar Sina Company in Iran. The results indicated that integrated planning in P-D, taking into account the product groupings and quality loss throughout the SC, would result in higher chain responsiveness and thus reduce the overall SC costs in the long run.

The rest of the paper is organized as follows. In Section 2, the focus is on some relevant works on the integrated P-D and quality models in SC. In addition to illustrating the PSO-based solution used, Section 3 presents the problem statement or the proposed approach of the research and the mathematical modeling applied. In Section 4, the case study is presented, and the results are analyzed in Section 5. Finally, Section 6 is dedicated to the conclusion and suggestions for future research.

2. Literature Review

From an overall perspective, the integrated P-D focuses on two distinct stages. The first stage is the production phase which converts the inputs into the final products and reduces all production costs, including setup costs, regular working hours, and overtime. The second stage is related to the distribution network of the final goods from production places to the customers aiming to reduce the costs of transportation, warehousing, etc. [6].

Fahimnia et al. [3] presented a review paper on this subject, categorized these models into seven according to the complexity of the modeling, and discussed the solution approach. Abid et al. developed a novel model of integrated P-D in a stochastic intermodal SC focusing on two points: minimization of overall costs and maximization of the level of satisfaction of customers. They propose a biobjective

stochastic model for handling uncertainty in demands as well as production capacities [7]. Ma et al., using bilevel programming for modeling the problem, proposed a model for a real case study [8]. Rafiei et al. presented a biobjective model that integrates suppliers, producers, distributors, and end users in four levels whose objective is minimizing the total cost of SC and maximizing the service level of the chain [9].

Also, managing deterioration is a remarkable topic in SC about which many studies have been conducted. Perishability is defined as the deterioration, decay, damage, spoilage, evaporation, obsolescence, waste, loss of utility, or loss of marginal value of a commodity that results in decreasing the usefulness of the original product [10]. According to this definition, all the products whose value is reduced over time are categorized under this class. The first study on perishability was carried out by Whiting [11]. Readers can find a comprehensive review of deterioration models in SC from previous research [5, 12–15]. Some problems arise in SCM due to the perishability of food products. According to Nematollahi and Tajbakhsh, a large proportion of reviewed studies focus on food quality and safety issues [16]. Also, the perishability and quality of food products are among the essential factors in managing the food SC from the stages of production to storage and finally to transportation [17]. Thus, both product flow and product quality affect SC performance. As a result, it is vital to adopt an integrative approach to control the food quality from producers to the final customers. In the integrated P-D model proposed by Jia et al., no deterioration occurs at the facilities, but different quality degradation processes are noticed in the transportation and sales stages. Moreover, shelf life is considered constant and definite [18]. Zhang et al. proposed an innovative idea for the integration of product quality. They assume three stages for the SC in their model where a function of time and temperature is adopted to represent the quality of food products for production, storage, and transportation [19].

The recent decade has witnessed a proliferation of new models for perishable items. The first model was introduced in [20], which included an integrated allocation and distribution design for deteriorating items supposed to be distributed in different locations with random demands. Later, the topic drew the attention of other scholars. The product quality was taken into account throughout the processes of P-D planning using the MIP model by [17] as well. He et al. [21] focus on the models of quantitative operations management associated with the management of food quality and classify the literature into four problem categories of storage, distribution, and pricing (for perishable food products), as well as operations management (for food traceability and safety). Yang and Tseng proposed a model considering deterioration for chilled food with an eye to the model of Gompertz, which illustrates the growth degree of microorganisms with time. Moreover, they take the rate of deterioration dependent on temperature and conduct a case study on pork sandwich [22]. The multi-objective framework was proposed at the operational level with an eye on two types of perishable goods fixed and loose

shelf life in the previous studies [23]. The researchers have also offered a new solution using the adaptive large neighborhood search framework to deal with the MILP model of integrated P-D planning for perishable products. In this study, the planning phase included lot sizing, scheduling, and line assessment decisions, whereas the distribution planning phase entailed the problem of vehicle routing with time windows [24]. With a focus on inventory planning, Priyan and Uthayakumar investigated the fuzzy deterioration in modeling integrated P-D. Furthermore, they viewed the setup cost as a function of capital expenditure that can reduce extra investment [25]. Rezaeian et al. suggested a new MINLP model for integrated P-D and inventory planning of fixed life products in a two-echelon SC. Also, the multivehicle and FIFO systems were considered in these models, and the combination of genetic algorithm and Taguchi method was employed for solving the problem [26].

The main target of deteriorating SCs is to keep the quality of products while improving their logistic performance and pay the highest attention to temperature as a delicate feature; therefore, an integrated production routing model was developed for perishable products. In this model, various factors, including the production, inventory, temperature of storage, and routing, as well as the temperature of the vehicle were considered [27]. A four-objective mixed-integer linear programming model was developed for an intelligent food logistics system. The goal was to first minimize total system expense, Co2 emission amount during transportation, and production, as well as total weighted delivery lead time and the second was to maximize the average quality of food. To solve the model, a modified multiobjective PSO algorithm with multiple social structures was developed [28].

As an overview of this section, it can be concluded that the models developed in this area can be divided into three categories. The first category is related to integrated P-D models that do not take into account the assumption of the perishability of goods. The second category includes models that focus on perishability but apply this assumption in either production or distribution models. The third category that includes only a few models and is more relevant to the present study, which includes integrated P-D models that consider the assumption of perishability, either as deterioration or as quality degradation. The main difference between the presented model and the above models is in the direct calculation of product quality (based on temperature and time) over a continuous period, the ability to be developed for multiple products, and adaptation to real-world problems.

3. The Problem Statement and Proposed Model

The modeling approach is based on a two-echelon SC that consists of manufacturing plants and customer centers shown in Figure 1.

According to Figure 1, the presented model is related to the two-echelon SC. At one echelon, there are manufacturing plants that meet all the assumptions associated with

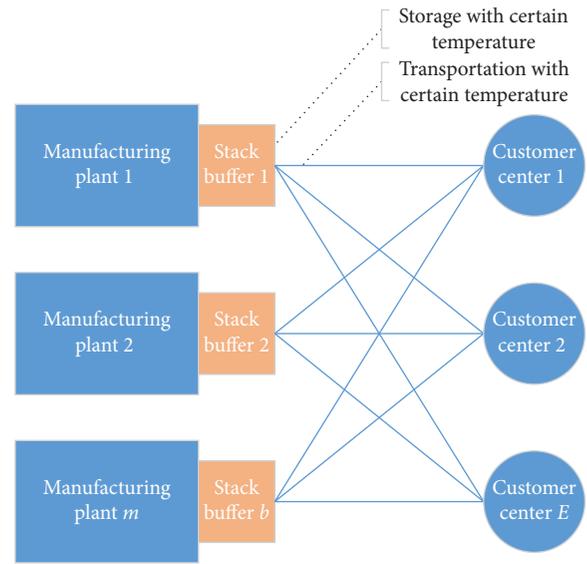


FIGURE 1: The scope of the proposed model.

production such as working in regular time, overtime, outsourcing, setup costs, and capacity constraints. At the other echelon, some customers have a specific demand that depends on the quality of the products. The problem is modeled based on the MOMINLP mathematical model whose results are as follows: grouping products in factories and determining the amount of production in each unit, choosing the optimal production method, choosing the best route to send products from manufacturing plants to customers in a way that the quality of the products delivered to customers increases, and reducing waste.

The SC relates to food types that have a perishable nature and lose their quality over time. This quality is stated as a function consisting of the rate of deterioration and the reactions' order. The food quality (q) is stated as

$$\frac{dq}{dt} = kq^n, \quad (1)$$

where q shows product quality, t shows the elapsed time, and n as a power factor known as the reactions' order is 0 (reaction with zero-order) in the case of fresh fruits or vegetables or 1 (reactions with first-order) in the case of meats as well as dairy products. The quality of the products decays linearly if $n = 0$ and exponentially if $n = 1$ [29]. Also, k is the rate of degradation developed by the Swedish chemist Svante Arrhenius in 1899. He combined the concepts of activation energy and the Boltzmann distribution law into one of the most essential relations in physical chemistry as follows [30]:

$$k = k_0 \cdot e^{-E_a/RT}, \quad (2)$$

where k_0 is a constant and called the pre-exponential factor independent from temperature, E_a the activation energy, R the gas constant which equals $8.314 \text{ J mol}^{-1} \cdot \text{K}^{-1}$, and T the absolute temperature, where RT is the average kinetic energy.

The quality of a product can be estimated at a certain point in the P-D network, according to the initial quality (q_0), subsequent storage timespans $i = 1, \dots, m$ with the time interval t_i , and degradation rate k_i (determined by the temperature T_i), which results in

$$q = q_0 \cdot \exp \left[- \sum_{i=1}^T k_0 t_i \cdot \exp \left[\frac{-E_a}{RT_i} \right] \right]. \quad (3)$$

With this equation, the expected quality of food products can be assessed after being stored and transported at certain timespans and temperatures [17].

3.1. Mathematical Modeling. As regards the nature of the integrated P-D problems, which may result in reduced product quality, a mathematical model was developed with the following specifications.

Products of m factories lie within the g -class of quality. In each factory, production takes place in standard working hours or overtime while being partly outsourced whenever appropriate. Depending on the nature of the products manufactured, all products are dispatched to e customer centers immediately after production. As indicated by the Arrhenius equation, products can corrupt under the impact of any change in temperature and time.

To apply this relation to the model, the first and main objective function was formulated to increase the quality of the products delivered to the customer. Moreover, a condition was set for the constraints specifying that if the product quality was lower than the minimum defined, the product was considered as waste. In the meantime, some factors were considered in the transportation of products from factories to customer centers. The main one was transportation time, directly affecting the perishability, along with other parameters such as road tolls, traffic, and traffic congestion as secondary determinants which influence shipping costs. The model also entailed two objective functions: increased quality of products received by the customers and reduced P-D costs.

3.1.1. Assumptions. The following assumptions are adopted in the model:

- (i) The capacity of all manufacturing plants is known and limited
- (ii) The required level and minimum quality of each product grade for end users are known
- (iii) Production is performed only once at the outset of the period, and then, the products are directly sent to the end users
- (iv) The shortage is not allowed
- (v) Besides time, the shipping cost is affected by the amount of toll, road quality, traffic congestion, etc.
- (vi) At each stage of the chain, products lose their quality over time due to the activity of internal microorganisms

- (vii) The temperature is assumed constant in all stages of SC and quality degradation is only affected by time spent or transportation based on the Arrhenius equation
- (viii) The products have high quality just when produced in the manufacturing plants
- (ix) Factories offer customers their products in several quality grades

3.1.2. Indices, Parameters, and Decision Variables. The indices, parameters, and decision variables used throughout the paper are given below.

Indices:

m Manufacturing plants ($m = 1, 2, \dots, M$)

e End users ($e = 1, 2, \dots, E$)

g Products' quality grades ($g = 1, 2, \dots, G$)

Parameters:

RP_{mg} : unit's production cost in regular time for the product at manufacturing plant m having quality grade g

OP_{mg} : unit's overtime production cost for the product at manufacturing plant m having quality grade g

OS_{mg} : unit's production cost of outsourcing for the product at manufacturing plant m having quality grade g

R_{eg} : forecasted demand for the product with quality grade g at the end user e

O_m : fixed cost of opening and operating manufacturing plant m

TC_{meg} : transportation cost for the product at quality grade g from manufacturing plant m to end user e

T_{meg} : transportation time for the product at quality grade g from manufacturing plant m to end user e

λ_{mg} : capacity hours for production in regular time for the product having quality grade g at manufacturing plant m

λ'_{mg} : capacity hours for overtime production for the product having quality grade g at manufacturing plant m

Q_g^{\max} : the quality level of the product with grade g just after the production

Q_g^{\min} : the quality level of product with grade g that end user accepts

WC_g : waste cost for the product with quality grade g in period t

M : a large positive number

Decision variables:

P_{mg} : product quantity when manufactured in regular time at manufacturing plant m having quality grade g

P'_{mg} : product quantity when manufactured overtime at manufacturing plant m having quality grade g

P''_{mg} : product quantity when outsourced by manufacturing plant m having quality grade g

D_{meg} : quantity of product with quality grade g transported from manufacturing plant m to end user e

Y_{meg} : the binary variable which indicates the selection of path of manufacturing plant m to end user e

W_g : waste amount of product with quality grade g

Z_m : the binary variable of operating manufacturing plant m

3.1.3. Model Formulation.

$$\text{Max } Z_1 = \sum_m \sum_e \sum_g Y_{meg} \left(Q_g^{\max} \exp \left[- \sum_{i=1}^{T_{meg}} k_0 t_i \exp \left(\frac{-E_a}{RT} \right) \right] \right), \quad (4)$$

$$\text{Min } Z_2 = \sum_m O_m Z_m + \sum_m \sum_g \left(RP_{mg} P_{mg} + OP_{mg} P'_{mg} + OS_{mg} P''_{mg} \right) + \sum_m \sum_e \sum_g Y_{meg} D_{meg} TC_{meg} + \sum_g WC_g W_g, \quad (5)$$

which subject to

$$\sum_m \left(P_{mg} + P'_{mg} + P''_{mg} \right) \geq \sum_e R_{eg}, \quad \forall g \in G, \quad (6)$$

$$\sum_e D_{meg} = P_{mg} + P'_{mg} + P''_{mg}, \quad \forall m \in M, \forall g \in G, \quad (7)$$

$$\sum_m D_{meg} - W_g = R_{eg}, \quad \forall e \in E, \forall g \in G, \quad (8)$$

$$W_g = \sum_m \sum_e D_{meg} Y_{meg} \quad \forall g \in G, T_{meg} \geq \gamma_g, \text{ where } \gamma_g = \frac{-\text{Ln}(\exp(-\beta_g t_0) - \beta_g Q_g^{\min})}{\beta_g} \& \beta_g = k_0 e^{[-E_a/RT]}, \quad (9)$$

$$P_{mg} \leq \lambda_{mg}, \quad \forall m \in M, g \in G, \quad (10)$$

$$P'_{mg} \leq \lambda'_{mg}, \quad \forall m \in M, g \in G, \quad (11)$$

$$\sum_g P_{mg} \leq M \cdot Z_m, \quad \forall m \in M, \quad (12)$$

$$\sum_g P'_{mg} \geq Z_m, \quad \forall m \in M, \quad (13)$$

$$P'_{mg} \leq P_{mg}, \quad \forall m \in M, g \in G, \quad (14)$$

$$MY_{meg} \geq D_{meg}, \quad \forall m \in M, e \in E, g \in G, \quad (15)$$

$$M(Y_{meg} - 1) < D_{meg}, \quad \forall m \in M, e \in E, g \in G, \quad (16)$$

$$P_{mg}, P'_{mg}, P''_{mg}, D_{meg}, W_g \geq 0, \\ \text{int } \forall m \in M, e \in E, g \in G, \quad (17)$$

$$Z_m, Y_{meg} \in \{0, 1\}, \quad \forall m \in M, e \in E, g \in G. \quad (18)$$

The first objective function (equation (4)) in the above formulation aims to maximize the quality of the products made available to the customers. Equation (5) represents the second objective function consisting of fixed cost for operating facilities, regular time and overtime production cost, outsourcing expenses, and transportation, as well as waste disposal costs. Constraint (6) indicates that the demand of end users must be satisfied. Constraint (7) ensures that the shipping amount exactly equals the manufactured products.

Constraint (8) guarantees that the sum of goods shipped from factories to the final customers meets the customer demand following the waste deduction. Constraint (9) is used to determine the amount of waste in the chain extracted according to the Arrhenius equation [17, 30], such that, considering the minimum quality (Q_{\min}) available for each product, the maximum shelf life is estimated through (γ_g),

$$\xi_0 = k_0 \exp\left(\frac{-E_a}{RT}\right) \text{ then Max } Z_1 = \sum_m \sum_e \sum_g Y_{meg} \left[Q_g^{\max} \exp\left(-\sum_{i=1}^{T_{meg}} \xi_0 t_i\right) \right]. \quad (19)$$

As the above relation is nonlinear and exponential, it can be transformed into a quadratic function using the Taylor series as follows:

$$\exp\left(-\sum_{i=1}^{T_{meg}} \xi_0 t_i\right) = 1 - \sum_{i=1}^{T_{meg}} \xi_0 t_i + \frac{\left(\sum_{i=1}^{T_{meg}} \xi_0 t_i\right)^2}{2} - O(x^3). \quad (20)$$

According to the results of the low-dimensional model solution, the $O(x^3)$ value is minimal and negligible. Therefore, the following relation can be considered as an alternative for the original with good approximation:

$$\text{Max } Z_1 = \sum_m \sum_e \sum_g Y_{meg} \left[Q_g^{\max} \exp\left(-\sum_{i=1}^{T_{meg}} \xi_0 t_i + \frac{\left(\sum_{i=1}^{T_{meg}} \xi_0 t_i\right)^2}{2}\right) \right]. \quad (21)$$

and if the product time in the chain exceeds this value, it is considered a waste. Constraints (10) and (11) show the production capacity in the manufacturing plant, while constraints (12) and (13) ensure that factories are viewed as operating in case they are engaged in the production process. Constraint (14) ensures that overtime production is allowed if it is carried out at a regular time. Constraints (15) and (16) ensure that shipping occurs between factories and customers if the lane is selected. The remaining constraints, i.e., (17) and (18), are nonnegativity, binary, and integer constraints on the decision variables.

3.2. Simplification of the Model. Since this model assumes a constant temperature, the first objective function can be simplified as follows:

As it is clear, the objective functions Z_1 and Z_2 go against each other. Namely, improvement in each function results in a departure from the optimal point by the other. Therefore, the simultaneous optimization of each of the given objective functions requires a specific method [31]. The GCM was employed in the current case to detect the minimization point for the totality of the relative deviations of the entire objective functions from the optimal values (Z_i^*). The ultimate objective function, calculated using the GCM, is given in relation (23):

$$\text{Min } Z = w_1 \times \frac{Z_1^* - Z_1}{Z_1^*} + w_2 \times \frac{Z_2 - Z_2^*}{Z_2^*}, \quad (22)$$

$$\text{Min } Z = w_1 \times \frac{Z_1^* - \left\{ \sum_m \sum_e \sum_g Y_{meg} \left(Q_g^{\max} \exp\left[-\sum_{i=1}^{T_{meg}} k_0 t_i \exp(-E_a/RT)\right] \right) \right\}}{Z_1^*} + w_2 \times \frac{\sum_m O_m Z_m + \sum_m \sum_g \left(RP_{mg} P_{mg} + OP_{mg} P_{mg}' + OS_{mg} P_{mg}'' \right) + \sum_m \sum_e \sum_g Y_{meg} D_{meg} TC_{meg} + \sum_g WC_g W_g - Z_2^*}{Z_2^*}. \quad (23)$$

According to this method, the objective functions can receive different weights to reveal the ideas of decision makers (DM). In this relation, w_i refers to the weight of the objective function determined by DM, while the sum of all weights equals 1. Based on this method, if a higher weight is assigned to a function by the DM, the solution will be closer to the optimal level of the given function. An independent calculation was performed for the optimal values of all functions (Z_i^*) in equation (23). In this stage, the objective functions which required maximization were normalized based on $(Z_i^* - Z_i)/Z_i$. Also, the normalization of the objective functions which needed minimization was conducted using $(Z_i - Z_i^*)/Z_i^*$.

3.3. Solution Procedure. This study developed a mixed-integer nonlinear formulation for the two-echelon SCs based on the integration of aggregate P-D plans and the concept of perishability. For solving this complex model, first, the GAMS optimization software was used and test runs were performed on a 2.33 GHz Core i5 with a 4 GB RAM system. The results were not applicable because the model was complex and the solution time was too long. Therefore, metaheuristic PSO was applied to solve the model within a more acceptable timespan.

To detect the optimal solution in the PSO algorithm, the initial population was generated at random. Given the constraints of the problem and its discrete nature, the probability for the random population generated to fall out of the limitations was very high. Therefore, the production of the initial population was performed such that the solution was kept within the range of the answer. To this end, several factories were randomly activated so that the minimum distance from one of the active factories to the customer was less than the product loss threshold. In this case, at least one factory was kept active to meet the needs of customers, so the limitation of satisfying customer needs was met.

After determining the active factories, customer demand was allocated to the factories. To this end, a percentage of customer demand was assigned to a randomly selected active manufacturing plant at any time, and this amount was deducted from the customer demand. This loop continued until all the demands were allocated to the factories. Next, the demands allocated to the factory were divided, due to the limitation of production capacity in regular hours, overtime, and during outsourcing. In this way, all the constraints of the problem were fulfilled, and the initial population was produced within the acceptable problem space.

In the PSO algorithm, the generation of subsequent solutions occurs through the movement of the initial population solutions. That is, the new birds' position (next-generation solution) is calculated based on the previous position, the distance to the best bird of the current generation, and the distance to the best bird among all generations. Structured matrices are used in the proposed algorithm to represent solutions, where each of the decision variables is a property of the matrix. In other words, a position is assumed for the bird for each of the decision variables. Similarly, a velocity vector is developed for each decision variable. Using the position and motion of the vector of the decision variables in the

initial population, the birds move and these steps continue until the stopping condition is fulfilled.

There are some parameters of control that affect the PSO algorithm. They include the problem dimension, particle numbers in each generation, coefficients of acceleration, weight of inertia, size of the neighborhood, and iteration frequencies, as well as random values. Moreover, in the case of the adoption of velocity constriction, PSO performance is impacted by the maximum coefficient of velocity and constriction. The control parameters used in the problem under study are listed in Table 1:

4. The Illustrative Case Study

To study the performance of the model, a case study was conducted at Protein Gostar Sina Company in the poultry industry which is one of the largest companies in Iran producing meat and protein. In the sector dealing with the production of poultry products, the company has seven slaughterhouse units and 25 customer center units throughout Iran, which are increasingly growing and expanding. Based on the type and quality of input materials, as well as slaughter and packaging conditions in the slaughterhouses, hot poultry products of this company fall into three quality grades: A, B, and C. Grade A contains the best quality products, without any problems in the process of slaughter and packaging. Grade B includes products that are not cut correctly during the slaughter process and have so-called contusion and ecchymosis. Finally, grade C includes products that have undergone some problems in the process of slaughter and packaging and contain contusion, ecchymosis, blood, and remainders of poultry trachea, esophagus, and some viscera in the packaging.

Modeling the P-D process of the company was carried out at a single time. In practice, live chickens ready to be slaughtered were loaded and shipped to the slaughterhouse during the night before slaughter. The slaughter normally took place during the night and the packaging process ended by morning. After completing the packaging process, the product had to reach the final customers within a maximum of 72 hours, and the model was designed to reduce the time of product delivery to the customer. However, it must be kept in mind that meat products could become corrupt over time due to the activities of internal microorganisms. This factor was taken into account in this study by using the Arrhenius equation. The model examines the effect of the factors of time and temperature on the growth of these microorganisms and the product quality reduction. For meat products, these quality changes occur exponentially. Due to the use of refrigerated machines and storage in particular refrigerated areas, the temperature factor was assumed to be constant at 4°C. Thus, the only factor in product corruption and the quality decrease was time.

As for the importance of the final quality of the product delivered to the customers and according to industry experts, the minimum acceptable quality for the three quality grades of manufactured products equals 0.4, 0.3, and 0.2. Also, the objective function coefficients, including values w_1 and w_2 in this model, respectively, equal 0.65 and 0.35. The

TABLE 1: Control parameters in PSO.

Particle numbers	100
Iteration frequencies	100
Coefficients of acceleration	$c_1 = 2, c_2 = 2$
Weight of inertia	1
Size of neighborhood	Particles at a distance of 2 units from one another

TABLE 2: Values of the production parameters.

Manufacturing plant	Grade A			Grade B			Grade C			$O (* 10^5)$	$\lambda (\lambda = 2\lambda')$	OS
	RP	OP	OS	RP	OP	OS	RP	OP	OS			
m_1	457	554	750	408	522	720	362	495	690	25	30,000	
m_2	423	541	735	390	510	720	343	485	660	23	30,000	
m_3	415	530	700	380	505	670	320	485	650	20	40,000	
m_4	423	545	750	390	510	730	343	500	700	25	20,000	
m_5	400	520	720	370	500	700	340	480	690	25	30,000	
m_6	480	580	800	465	580	780	450	580	760	35	50,000	
m_7	510	600	800	490	600	780	470	600	760	30	40,000	

TABLE 3: Values related to the customer demand.

R	e_1	e_2	e_3	e_4	e_5	e_6	e_7	e_8	e_9	e_{10}	e_{11}	e_{12}	e_{13}	e_{14}
GA	950	1420	950	1400	2800	1890	675	540	815	675	1100	500	1000	5000
GB	330	500	340	500	1000	675	243	193	286	243	900	750	1500	20,000
GC	700	100	700	100	200	260	490	390	430	490	400	1000	400	20,000
	e_{15}	e_{16}	e_{17}	e_{18}	e_{19}	e_{20}	e_{21}	e_{22}	e_{23}	e_{24}	e_{25}			
GA	8000	7500	9500	9000	7500	1150	4700	4000	7000	6500	12000			
GB	3000	2700	3400	3000	2700	400	1700	2000	2500	3000	9100			
GC	600	600	700	700	550	80	340	3500	1000	7000	10,000			

* denotes GA = Grade A, GB = Grade B, and GC = Grade C.

values of the waste cost for the decayed items for each quality grade also equaled 6000, 5200, and 4700, respectively. Other dimensions of the problem include those of production such as factory setup costs, production at a regular time, overtime, or outsourcing, and quantitative limitations which are listed in Table 2:

The values for customer demand are also presented in Table 3.

Other model-related parameters are given in Supplementary Materials (available here).

5. Result Analysis

The following procedures were used to estimate the model performance. Initially, the model developed for the case study referred to in Section 4 was solved solely with the second objective function and only with the emphasis on cost reduction. The results indicated that the objective function value was equal to $8.9 * 10^7$ and the production units 2, 3, 4, and 5 started working (Figure 2). However, when the model was solved with two objective functions, while simultaneously minimizing costs and enhancing product quality, the value of the second objective function

equaled $10.4 * 10^7$, and the production units 1, 2, 4, and 5 initiated production.

By carefully examining the production and allocated values in both cases, it became clear that, in the dual-purpose case, the total time spent on delivering the products to customers was less than the single-objective state. This indicates an increase in the quality of the products offered to the customers. Nowadays, the increasing importance of the use of healthy food products, high value of quality, and customer dissatisfaction have given a pivotal role to the quality and prevention of excessive reduction of the product quality in the SC.

Since the initial model was a MOMINLP and the solution time was not justified for large-scale problems, two steps were considered: first, the nonlinearity of the problem with part 3.2 transformation from exponential to the second-order problem, and second, the development of PSO algorithm to solve the larger samples. To investigate the performance of the developed solutions, random samples with different sizes were generated with varying factory and customer numbers and solved using all three methods (main model, quadratic function, and PSO). The results are summarized in Table 4. Items related to the 5th rows are justified if the sales policy is direct.

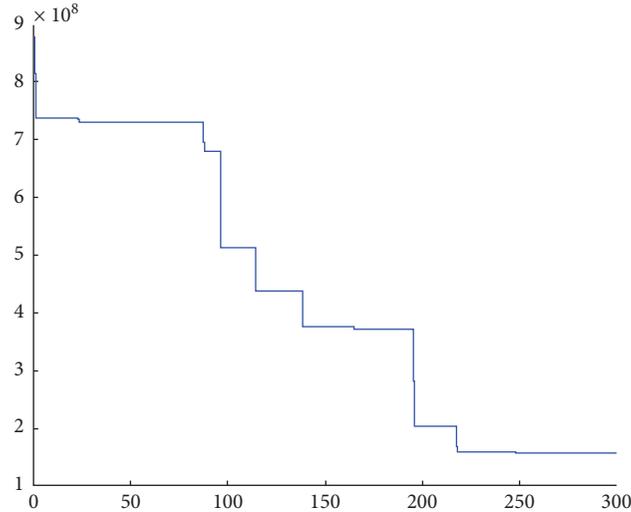


FIGURE 2: The result of PSO.

TABLE 4: The results of solving random samples with different methods.

No	Number of manufacturing plants	Number of customers	Time to solve (second)/ deviation from global solution (%)				
			Main	Quadratic	PSO		
1	10	30	60	45	0	70	0
2	10	50	110	87	0	75	0
3	20	100	320	183	0	92	2
4	20	200	1270	582	0	180	4
5	20	500	3850	1300	0	225	3.7
6	20	700	12,000	4300	0	310	5.2
7	20	1000	58,000	6400	0	390	4
8	20	5000	—	18,600	0	840	—
9	20	10,000	—	—	—	1200	—
10	20	50,000	—	—	—	3740	—

6. Conclusion

The development of integrated models in the food SC on the one hand and the increased demand for healthy food on the other have doubled the need to develop integrated models for enhancing the quality of products. In this study, a new integrated P-D model was developed with a focus on the quality of products in the SC of perishable materials. For validation, the model was implemented in the poultry industry. Model solutions were developed and applied to improve efficiency, which ultimately led to increased quality of products throughout the chain. The research findings can be summarized as follows:

- (i) The integrated P-D models play an essential role in creating integrity in SC decisions if they are adapted and used in operational cases. These models can be used as a management decision support system (DSS) that helps managers in decisions at different time intervals. For example, if the current status is compared to the optimal one, an overall estimate of the reasons for customer dissatisfaction can be observed and, in

coordination with the quality assurance unit, appropriate corrective actions can be taken. Moreover, by examining the costs in the optimal status of the model and matching them with the costs of the financial unit, a suitable budgeting plan can be devised.

- (ii) Among the models developed to estimate the quality of products in the SC, the Arrhenius equation is most capable of adapting to real-world problems due to its simplicity and distinct categorization. It seems that the capabilities of the model can be used more extensively in complementary models in the future, which certainly will require a focus on solution methods.
- (iii) Based on the Arrhenius equation, temperature and time are among the most influential parameters in the quality of products and materials. By adopting effective solutions, these two factors can be substantially controlled in the chain. Future studies can delve further into the nature of the relation between the given factors and the use of modern packaging methods, equipped transportation systems, and food warehouses.

Data Availability

The data used to support the findings of this study are included within the article.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Supplementary Materials

Supplementary Table 1: the table represents transportation time for products at quality grade *g* from manufacturing

plant m to end user e . g_1 , g_2 , and g_3 represent quality grades A, B, and C, respectively, in the case study. Supplementary Table 2: the table describes transportation cost for the products at quality grade g from manufacturing plant m to end user e . g_1 , g_2 , and g_3 represent quality grades A, B, and C, respectively, in the case study. (*Supplementary Materials*)

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