



Multi-objective sustainable supply chain with deteriorating products and transportation options under uncertain demand and backorder

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Abstract. Supply chain sustainability, with economic, environmental, and social values, has gained attention in both academia and industry. For deteriorating and seasonal products, like fresh produce, the issues of timely supply and disposal of the deteriorated products are of great concern. This paper is to develop a possibilistic mathematical model, solved after linearizing the non-linear statements, and to propose a new replenishment policy for a centralized Sustainable Supply Chain (SSC) for deteriorating items. Different transportation vehicle options, which produce various pollution and greenhouse gas (GHG) levels, are considered. Several variables such as the end-customer demand, the partial backordered ratio, and the deterioration rate are uncertain. Deterioration occurs for in-stock inventories and during transportation. The solution provides the optimum transportation modes and routes, and the inventory policy by finding a balance between financial, environmental, and social criteria.

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1. Introduction

“A supply chain is a system of organizations, people, technology, activities, information, and resources involved in moving a product or service from supplier to customer” [1]. Adding the ‘green’ concept to the ‘supply chain’ concept creates a new paradigm, where the supply chain will have a direct relation to the environment [2]. The green SCM concept is further developed into sustainable SCM to include social features of the supply chain as well as environmental and economic aspects.

There has been growing concern about the environmental and social footprints of business operations. People are conscious of the world’s environmental problems, such as pollution, global warming, toxic

substance usage, and non-renewable resources [2]. The majority of papers in supply chain network design focus on economic performance. Recent studies have considered environmental dimensions. There is a gap in quantitative models of social factors with environmental and economic impacts [3].

Uncertainty is an inherent attribute of supply chains, which affects the supply chain’s performance and complexity. Numerous methods exist for quantitative description of supply chain uncertainty in the literature, most generally involving interval analysis [4], possibilistic and fuzzy sets methods [5], stochastic programming methods [6], etc.

Transportation is a major factor in deteriorating products supply chain, as deterioration and economic and environmental factors depend on the distance and condition of product transportation. To reduce purchase costs and attract a larger base of customers, retailers, such as WalMart, Home Depot, and Costco, are constantly seeking suppliers with lower prices and

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finding them at greater distances from their distribution centers and stores [7].

This paper employs many of the recent aspects of deteriorating products SCM. It simultaneously considers economic, environmental, and social objectives; transportation and route options; uncertain demand; deterioration and backorder ratios; and non-linear sale price discount. Deterioration can occur both in in-stock inventories and during transportation in the model. Deterioration during transportation is a function of transportation type (truck vs. airplane, refrigerated vs. individually packed, etc.) and transportation routes. A possibilistic approach is used to find the optimum solution for a centralized supply chain, where the leftover product is disposed of for a given amount of cost or profit. These distinct features are used simultaneously to provide a holistic model and reach an applied solution. The main research question is the impact of the social factors introduced in the model, combined with the economic and environmental impacts. A fresh produce center in Tehran, Iran, was used to gather data and test the model.

In the next two sections, various relevant aspects of SCM used in our research, i.e. Sustainable Supply Chains (SSC), deteriorating products, and fresh produce, are reviewed. Section 4 presents the problem description, including notations and assumptions, followed by the sections on the mathematical model, solution approach, numerical analysis, and conclusions.

2. Literature review

The literature review is presented in two sub-sections: We first review some of the main studies on SSC, and then assess some major research on replenishment policies for deteriorating products.

2.1. Sustainable supply chain

The Brundtland Report [8] underlined the importance of sustainable development and called for “a better life for everyone without destroying the natural resources for future generations”. Since then, the concept of sustainability has been broadened to include Planet, People, and Profit [9]. It may be argued that “Sustainable Development” and “Sustainability” are not essentially the same. Accordingly, the former is concerned with processes while the latter is considered as a state. These two terms are frequently used interchangeably in the literature without highlighting the differences [10]. In this paper and most other studies in the supply chain literature, the concept used is sustainability.

Organizations are increasingly assimilating sustainability into their SCM practices. Although the motivations of individual organizations may vary, key objectives generally include an interest in achieving sustainable streams of products, services, information,

and funds to provide maximum value for involved stakeholders [11].

According to [12], Sustainable SCM (SSCM) is “the management of material, information, and capital flows as well as cooperation among companies along the supply chain while integrating goals from all three dimensions of sustainable development, i.e., economic, environmental, and social, which are derived from customer and stakeholder requirements.”

Table 1 shows an illustrative sample of recent papers in the area of SSC. While this is by no means a representative sample of all existing research in the literature, it is sufficient to illustrate the gaps and deficiencies in the current research. For a more comprehensive review of studies in the field of SSCs, interested readers are referred to [13]. According to Table 1, the related literature can be characterized in three groups based on the direction of material flows:

- i) Forward Logistic (FL): Many researchers have considered the sustainability concept in forward logistic processes (conventional logistic) where after procuring from suppliers, raw materials are converted to finished goods at manufacturer sites and, subsequently, transferred to customers via distribution centers to fulfill their demands [14]. Brandenburg et al. [13] provide a review of 134 papers on quantitative, formal models that addressed sustainability aspects in forward supply chains;
- ii) Reverse Logistic (RL)/Backward Logistics (BL): These studies consider the flow of used or returned products from the customers back to the collection centers for reusing, remanufacturing, recovering, disposal, etc;
- iii) Closed-loop supply chains: These studies, such as [3,5,15], consider a supply chain network by integrating the forward processes with the backward processes.

In addition, many SSCM quantitative models developed for uncertain conditions come from various sources like demand, capacities, costs, etc. Based on Sazvar et al. [6], there are four main approaches for considering uncertainty in the decision-making process: robust optimization, stochastic programming, fuzzy programming, and stochastic dynamic programming.

As Table 1 shows, very few studies take into account multiple sustainability dimensions as compared to studies developed in green supply chains (considering economic and environmental criteria). Many studies present real-world cases from the pharmaceutical, medical, glass, food, etc. industries to demonstrate the applicability of their developed models. However, limited research has explicitly addressed an important category of products called deteriorating items. In the

Table 1. Illustrative sample of research on sustainable replenishment.

Year	Author(s)	Modelling approach	Characteristics: Forward/backward	Application in real cases	Uncertain parameters	Economic criteria	Environ. criteria	Social criteria
2010	Pishvae Torabi & [5]	Possibilistic prog.	Forward/backward	—	Costs, capacities, demands, rates of return products	Min total costs	—	Total delivery tardiness
2014	Validi et al. [20]	Mixed integer prog.	Forward	Food industry	—	Min total costs	Min. CO ₂ emission	—
2011	Pishvae, et al. [21]	Robust possibilistic prog.	Forward	Medical industry	Costs, demand, capacities	Min total costs	—	Max social responsibility
2014	Sazvar et al. [6]	2-stage stock prog.	Forward	Pharmaceutical industry	Demand	Min total costs	Min. GHG emission	—
2011	Wang et al. [22]	Mixed integer prog.	Forward	A procurement center	—	Min total cost	Min. CO ₂ emission	—
2015	Das and Posinasetti [15]	Mixed integer program, goal prog.	Forward/backward	—	Returned products to the retailer (scenario based)	Max total profit	1-min. spent energy -Min. harmful emission	—
2010	El-Sayed et al. [23]	Multi-stage stochastic prog.	Forward/backward	—	Demand	Max total profit	—	—
2014	Devika et al. [3]	Mixed integer prog.	Forward/backward	Glass industry	—	Min total costs	Min. CO ₂ emission	Max social responsibility
2010	Jamshidi et al. [24]	Mixed Integer Prog.	Forward	—	Demand	Min total costs	Min produced dangerous gases (NO ₂ , CO, volatile organic (VOCs))	—

next sub-section, in Table 2, the literature on these types of products is reviewed.

2.2. Deteriorating products

Deterioration of goods is a common phenomenon. Pharmaceuticals, blood, flowers, fruits, vegetables, dairy, meat, and foods are just a few examples. Perishable models have been widely studied in recent years. The literature on perishable product SCM has

skyrocketed. Deterioration is defined as the damage, spoilage, vaporization, dryness, etc. of items [16]. Continuously deteriorating items suffer loss in quantity or in quality. This is distinct from obsolescence, or sudden death, where items lose their value because of rapid change in technology, introduction of a new product, or going out of fashion [17]. Ghare and Schrader [16] were among the first to study deteriorating products and developed an inventory model

Table 2. Illustrative sample of research on deteriorating products replenishment.

Year	Author	Solution approach	Demand function	Deterioration function	Inventory system	Shortage PB: partial backorder	Planning horizon	Objective function
2014	Kim et al. [26]	Exact-simulation	Constant	Inventory dependent	FOQ	Backorder	Infinite	Min cost
2011	Wang et al. [33]	Heuristic	Constant	Time dependent	FOQ/FOI	NO	Infinite	Min cost
2011	Wee et al. [34]	Exact	Constant	Constant	FOQ/FOI	NO	Finite	Max profit
2010	He et al. [35]	Exact	Time dependent	Constant	FOQ/FOI	NO	Finite	Min cost
2009	Wee and Chung [36]	Exact	Constant	Constant	FOI	NO	Infinite	Min cost
2008	Liao [37]	Exact	Constant	Constant	FOQ	NO	Infinite	Min cost
2008	Urban [38]	Heuristic	Inventory dependent	Non-linear time dependent holding cost	FOQ/FOI	NO	Infinite	Max profit
2007	Dye [39]	Heuristic	Price dependent	Time dependent	FOQ	P.B	Infinite	Max profit
2007	Mahata & Goswami [40]	Exact	A fuzzy number	A constant deterioration rate + A fuzzy holding cost	FOI	NO	Infinite	Min cost
2005	Dye & Ouyang [41]	Exact	Inventory dependent	Constant	FOI/FOQ	P.B.	Infinite	Max profit
1998	Luo [42]	Numerical	Price and advertisement dependent	Weibull	FOQ	Lost sale	Infinite	Max profit
1982	Weiss [43]	Exact	1- Constant, 2-Poisson	Non-linear time dependent holding cost	FOQ/FOI	NO	Infinite	Min cost

for exponentially decaying inventory. Amorim et al. [18] studied the effects of concurrent optimization of production and distribution for perishable products. Prastacos [19] published a survey of blood inventory management.

Bakker et al. [25] reviewed over 200 papers published in the last decade on deteriorating inventory systems. In Table 2, a summary of the main related research is presented. The types of demand, shortage, and deterioration functions for each study are reported. More details about some of the main assumptions, such as inventory system (Fixed Order

Quantity (FOQ)/Fixed Order Interval (FOI)), solution approach, planning horizon, and objective function types are also presented.

From Tables 1 and 2, it can be seen that little research deals with deteriorating products in SSCs in comparison with the research on products with unlimited lifetime. Sazvar et al. [6] developed a stochastic replenishment model in a centralized green supply chain for deteriorating items, with inventory and transportation costs and the environmental impact under uncertain demand. They found, because of the recycling of deteriorated items, the environmental

impact of deteriorating items was more significant than that of non-deteriorating ones. Kim et al. [26] studied a closed-loop supply chain where Returnable Transport Items (RTIs) were applied to ship deteriorating goods from the supplier to the buyer. Then, empty RTIs were collected at the buyers and returned to the supplier.

In summary, the main issues, like considering social criteria, deterioration during transportation, and effect of transportation paths, as well as vehicle types on deterioration process, are significantly challenging in the real world. However, to the best of our knowledge, less attention has been paid to quantitative studies.

2.2.1. Fresh produce

Fresh produce (fruits, flowers, and vegetables) is a fast growing segment of the economy, and exporting and importing of fresh produce are common phenomena [27]. The success factors in fresh produce SCM include continuous investment (despite tight margins), volume growth (providing confidence in the future), improvement of measurement and control of costs (in the pursuit of gains in efficiency), and innovation (the level of service and the way of doing business with key customers) [28].

The challenge in managing fresh produce is that product value deteriorates significantly over time at rates that are highly temperature- and humidity-dependent. The scope of most published studies is the post-harvest supply chain [38]. Agricultural issues like seed production and growing have not been explored. A decision about supply chain involves a choice between responsiveness and efficiency [28]. Blackburn et al. [29] found that supply chain should be responsive in the early stages and efficient in later stages.

For fresh produce, a retailer procures from a supplier a quantity of a fresh product, which must then be transported to reach the target market. The retailer has to make an appropriate effort to preserve freshness of the product, and may pay higher costs for better transportation [28]. In practice, it is common to offer deteriorated items at a discount price. In supermarkets, items near the expiration date are marked down to influence buying behavior the consumer [30].

Shukla and Jharkharia [31] presented a literature review of the fresh produce SCM, with processes from production to consumption. The main interest in fresh produce SCM is consumer satisfaction and revenue maximization, while post-harvest waste reduction is a secondary objective. Inaccuracy in demand forecasting, demand and supply mismatch, lesser integrated approach, etc. are of concern. Though social and environmental factors in fresh produce supply chain are major concerns, very little research exists at this time on developing a comprehensive SSCM model for these products.

3. Research gaps

Worldwide grocery retailers' sales in 2012 exceeded \$1,000 billion. Deteriorating products, such as fresh produce, dairy, and meat, account for more than a third of these sales [32]. Managing SCM of deteriorating products is progressively becoming more important. Today's customers request greater product diversity and price. Thus, more deteriorating products tend to exceed the best-before date, while demand and price per product tend to be less predictable. In addition to normal SCM costs (ordering, transportation, holding, and shortage), deteriorating items impose extra costs on the system.

Today, for many corporations, sustainability is a major factor for competitiveness and survival. The environmental factors, for deteriorating product manufacturers and retailers, not only come from transportation factors and GHG emissions, but also are a factor of disposal of spoiled and unused products. The social factors need to be considered equally and separately as parts of sustainability, too. Social factors, in particular for seasonal and highly volatile demand products, are becoming strategic issues. Firms can no longer easily hire and fire employees at will, ignore their welfare and training, impose unreasonable hours and working conditions, etc. For products traded internationally, local workers need specific treatment, by law and by social responsibility principles, so that work would not be sent offshore just because of cost or trade considerations. For deteriorating products, such as fresh produce, there is a mismatch between supply and demand, encouraging increasing imports and exports.

The motivation for this research comes not only from a lack of suitable work in the literature, but also from the growing importance of the above gaps in practice. Deteriorating items increasingly affect the lives of employers and consumers in the developed and developing countries, and are exceedingly creating issues in economic, environmental, and social fronts for corporations and politicians.

This research considers the sustainable supply chain planning problem for deteriorating products in a multi-period environment under: i) uncertain demand and ii) a price-discount scheme, and by considering iii) sustainability criteria, particularly social and human-resource related ones; iv) different transportation vehicle types as well as dependency of on-the-way deterioration rate to the vehicle types; v) different paths for transportation depending on on-the-way deterioration rate to the path types; and vi) various costs such as shortage, disposal, and human resource costs.

Reviewing the existing literature shows that though a great deal of research has been conducted on these types of problems, to the best of our knowledge, no holistic system has been developed to cover all

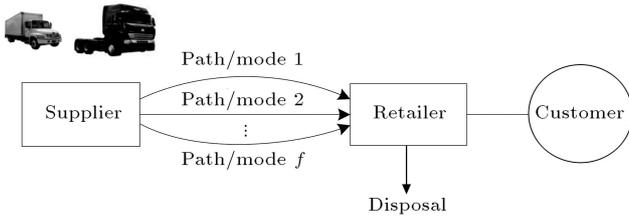


Figure 1. A schematic of the considered supply chain.

aspects of the above description. A broad range of such studies has been devoted to some of its aspects separately or to their specific combinations. Therefore, there is a gap between practical and theoretical contributions of deteriorating product’s SCM, and the aim of this paper is to bridge this gap by considering all the mentioned aspects in a centralized SSC.

4. Problem description

A centralized forward supply chain provides a deteriorating product, as shown in Figure 1. The supply chain consists of three kinds of entities: a supplier, a retailer, and customers. The planning horizon is finite and consists of multiple periods. At each period, a quantity order is supplied by the supplier and shipped to the retailer in order to respond to end-customer’s demand. Because of deterioration characteristics of the product, if inventory is left at the end of a period at the retailer site, $\hat{\theta}$ percent of it should be disposed. The end-customer’s demand (\tilde{D}) and deterioration rate of on-hand inventories ($\hat{\theta}$) are considered as uncertain parameters.

Since the demand rate (\tilde{D}) and deterioration rate ($\hat{\theta}$) are uncertain, shortage can occur at each period, which may be partially backordered. In this way, at each period, $\tilde{\beta}$ ratio of unfulfilled demands (if exists) can wait up to the next period, while the other $1 - \tilde{\beta}$ ratio will be lost. $\tilde{\beta}$ is assumed to be uncertain, too.

The supplier, providing the product, should ship it to the retailer. There are several transportation vehicle options available at the supplier site. Each one is characterized by its capacity, transportation cost, GHG emission, and the deterioration of on-the-way product. Each type of transportation vehicles has its technical specifications, which affect the product deterioration rate during transportation. Thus, the deterioration rate of on-the-way product is variable and depends on the vehicle type.

As in Figure 1, there are also various paths (or transportation modes) from the supplier to the retailer. In the real world, various types of vehicle and different paths are available to send goods from suppliers to retailers. The vehicle types/paths have a considerable influence on each product’s transportation cost, amount of GHG emission, and deterioration rate of product. For example:

- More modern and efficient transportation vehicles keep the product healthier and generate less GHG, but they incur higher costs;
- Sometimes, transportation by ship is faster and cheaper, but results in more disposals because of humidity. In contrast, overland paths cause fewer disposals, but are more expensive and slower;
- Sometimes, using vans is more rapid and more expensive, and thus, it results in low product disposal in comparison with using trucks.

In summary, there are two sources of deterioration: i) deterioration rate of on-hand inventory at retailer warehouse ($\hat{\theta}$) and ii) deterioration rate of on-the-way products ($\tilde{\eta}_{vf}$), which is affected by vehicles type (v) as well as transportation paths/mode features (f).

In many real cases, the selling price depends on the sale quantity. In this problem, the selling price (pr) is non-linearly dependent on the sale quantity by the following function:

$$pr = \begin{cases} pr_1 & SA_0 \leq S_t < SA_1 \\ pr_2 & SA_1 \leq S_t < SA_2 \\ \dots & \dots \\ pr_m & SA_{m-1} \leq S_t < SA_m \end{cases} \quad (1)$$

In Eq. (1), S_t indicates sale in period t . Also, $pr_1 > pr_2 > pr_3 > \dots > pr_m > 0$ and $SA_0 < SA_1 < SA_2 < \dots < SA_m$ are positive parameters. In other words, as the sale-quantity increases, the selling price decreases.

The objective is to find the best configuration of vehicle type, transportation path/mode, and order quantities in each period to simultaneously meet the following criteria:

- i) Maximizing the total profit (an economic objective);
- ii) Minimizing total GHG emissions (an environmental objective); and
- iii) Minimizing human recourse variations from one period to another (a social objective).

There is a need for employees to carry out the logistic activities, including transportation and other logistic activities, throughout the supply chain. In some periods, since the forecasted customer demand is very high, the order quantity and, consequently, the amount of required logistic activities throughout the chain increase in order to respond to demand. These logistic activities are packing products at the supplier, unpacking products at the retailer, repacking products at the retailer, issuing invoices, etc. The required transportation fleet and, thus, the labor needed may also increase. In such periods, usually, the number of

required workers is more than the number of workers available in the supply chain. In this way, either some extra labor must be hired or the supply chain managers accept leaving a part of the demands unsatisfied.

In contrast, in some periods, the forecasted demand is very low and, as a result, the order quantity and the volume of required logistic activities decrease in comparison with the previous periods. In such periods, the supply chain managers decide either to keep a number of workers inactivated or to fire them. In the production planning literature, adjusting resource levels (including human resources) to the volume of forecasted demands is called “chase strategy”. Some disadvantages of this strategy are reducing job interest, decreasing the job satisfaction and job security of workers, and increasing administrative costs related to high levels of hiring and firing. In this way, variations in labor levels from one period to another can be regarded as a significant social criterion in supply chains.

The opposite of chase strategy is “leveling strategy” where a fixed number of workers are kept through all periods regardless of changes in the forecasted demands. A main disadvantage of this strategy is high level of inactivated workers in some periods. Usually, the optimal strategy is somewhere between “chase strategy” and “leveling strategy”, which can be determined by the mathematical model developed in this paper by considering economic, environmental, and social criteria.

4.1. Assumptions

The following assumptions are also considered in developing the proposed mathematical model:

- The uncertain parameters, \tilde{D} , $\tilde{\beta}$, $\tilde{\theta}$, and $\tilde{\eta}_{vf}$, are fuzzy numbers;
- The retailer’s initial inventory (or shortage) level, I_0 (or B_0), can be positive, zero, or negative;
- Human resource level consists of two components: i) required human resource for transportation, called “transportation labors”, and ii) required human resource for doing other logistic activities (except transportation) through the supply chain, such as packing products at supplier, unpacking and repacking products at the retailer, etc. We have called these labors “logistic labors”;
- Purchase cost (c), holding cost (h), backorder cost (γ), lost sale cost (π), and disposal cost (SV) for a unit of product are given and fixed parameters;
- There is a limited number of vehicles of each type;
- The cost of disposal for each unit of product, SV , is defined by a multiple-breakpoint function as follows:

$$SV = \begin{cases} SV_1 & K_0 \leq \text{disposal quantity} < K_1 \\ SV_2 & K_1 \leq \text{disposal quantity} < K_2 \\ \dots & \dots \\ SV_p & K_{p-1} \leq \text{disposal quantity} < K_p \end{cases} \quad (2)$$

In the above function, each SV_i ($0 \leq i < p$) is a predefined parameter that can be positive, negative, or zero depending on the case. For example, deteriorated plastics or drugs are usually sold to recycling centers and, therefore, bring money for the system. In contrast, deteriorated fruits and vegetables have to be disposed, which is cost-generating. $K_0 < K_1 < K_2 < \dots < K_p$ are positive parameters. Finally, in Eq. (2), “disposal quantity” refers to two sources: i) on-hand inventories deteriorated in each period; and ii) on-the-way products deteriorated in each period.

4.2. Notations

The following notations are applied to develop the proposed model:

Indices

- t Index of time period, $t \in \{1, \dots, T\}$
- v Index of transportation type, $v \in \{1, \dots, V\}$
- f Index of path from supplier to retailer, $f \in \{1, \dots, F\}$
- m Index of sale quantity level, $m \in \{1, \dots, M\}$
- p Index of disposal level, $p \in \{1, \dots, P\}$

General parameters

- T Planning horizon length
- $\tilde{\theta}$ Deterioration rate of in-stock inventories
- $\tilde{\beta}$ Fraction of demand backordered during a stock-out
- \tilde{D}_t Demand in period t
- d_f Distance between supplier and retailer under path/mode f
- CAP_v Capacity of a type- v vehicle (defined by unit of product)
- $MAXT_v$ Maximum number of type- v vehicles available
- $\tilde{\eta}_{vf}$ Deterioration rate of product when it is transported by a type- v vehicle through path/mode f

Economic parameters

- O Fixed ordering cost for each replenishment
- OC_t Ordering cost in period t
- C A product unit purchase cost

- pr A product unit selling price
- h A product unit holding cost per period
- π Penalty cost of a product unit lost sale (including lost profit)
- γ Backordered cost of a product unit per period
- SV Disposal cost (or income) of a product unit
- TA_{vf} Cost of transportation by a type- v vehicle for each unit of distance through path/mode f

Environmental parameters

- G_{vf} GHG emission level produced by a type- v vehicle under path f
- GD GHG emission level produced by a unit of disposed product

Social parameters

- HT_v Required labor for using a type- v vehicle
- HUM Average number of products in each period for which a worker can do the related logistic activities (excluding transportation) and prepare them to deliver to the customers

Decision variables

- I_t Inventory level at the end of period t
- B_t Shortage level at the end of period t
- Q_t Net order quantity of period t received by retailer
- δ_{tvf} Gross order quantity of period t transported by a type- v vehicle through path f
- λ_t On-the-way inventories deteriorated in period t
- X_{tvf} Number of type- v vehicles used in path f in period t
- HU_t Number of labors required in period t
- S_t Total sale in period t
- Z_1 Total cost of the supply chain
- Z_2 Total GHG produced in the supply chain
- Z_3 Total variations in human resource

5. Mathematical model

The proposed mathematical model is developed in two steps: First, it is developed in a non-linear form, and second, the equivalent linear form of the non-linear mathematical model in the previous step is developed by applying some linearization techniques.

5.1. Non-linear mathematical model

In terms of the above assumptions and notations, the proposed model can be formulated as follows:

$$\begin{aligned} \text{Max } Z_1 = & \sum_{t>0} pr.S_t \\ & - \left(\sum_{t>0} (OC_t + C. \sum_{v,f} \delta_{tvf} + h.I_t \right. \\ & \quad + (1 - \tilde{\beta}).\pi.B_t + \tilde{\beta}.\gamma.B_t \\ & \quad + \sum_{v,f} (TA_{vf}.d_f.X_{tvf}) \\ & \quad \left. + SV.(\tilde{\theta}.I_t + \lambda_t)) + CH_t.HU_t \right), \end{aligned} \quad (3)$$

$$\text{Min } Z_2 = \sum_{t>0} \left(\sum_{v,f} (G_{vf}.d_f.X_{tvf}) + GD.(\tilde{\theta}.I_t + \lambda_t) \right), \quad (4)$$

$$\begin{aligned} \text{Min } Z_3 = & \sum_t \left(|HU_t - HU_{(t-1)}| + \sum_{t,v} HT_v. \left| \sum_f X_{tvf} \right. \right. \\ & \quad \left. \left. - \sum_f X_{(t-1)vf} \right| \right), \end{aligned} \quad (5)$$

s.t.

$$Q_t + (1 - \tilde{\theta}).I_{(t-1)} - \tilde{D}_t - \tilde{\beta}.B_{(t-1)} = I_t - B_t \quad \forall t, \quad (6)$$

$$I_t.B_t = 0 \quad \forall t, \quad (7)$$

$$OC_t = \begin{cases} O & Q_t > 0 \\ 0 & \text{otherwise} \end{cases} \quad \forall t \quad (8)$$

$$\lambda_t = \sum_{v,f} \tilde{\eta}.\delta_{tvf} \quad \forall t, \quad (9)$$

$$Q_t = \sum_{v,f} (1 - \tilde{\eta}_{vf}).\delta_{tvf} \quad \forall t, \quad (10)$$

$$(HU_t - 1) \leq \frac{\sum_{v,f} \delta_{tvf}}{HUM} \leq HU_t \quad \forall t, \quad (11)$$

$$\sum_{v,f} \delta_{tvf} \leq \sum_{v,f} CAP_v.X_{tvf} \quad \forall t, \quad (12)$$

$$\sum_f X_{tvf} \leq MAXT_v \quad \forall v, t, \quad (13)$$

$$X_{tvf}, HU_t \geq 0, \text{ integer} \quad \forall t, v, f, \quad (14)$$

$$Q_t, \delta_{tvf}, I_t, \lambda_t, B_t, S_t \geq 0 \quad \forall t, v, f, \quad (15)$$

Eq. (3) represents total profit, which is total revenue minus total cost. To calculate total revenue ($\sum_{t>0} pr.S_t$), the product selling price, pr , is defined based on Eq. (1). The total cost of system consists of ordering, procurement, holding, lost sale, backordering, transportation, disposal costs, and the wage of logistics worker, respectively. Without losing generality, it is assumed that the wages of the transportation worker are included in transportation costs of vehicles (TA_{vf}). As mentioned above, disposal cost consists of two parts: cost/income of on-hand inventories deteriorated ($\tilde{\theta}.I_t$) and cost/income of on-the-way inventories deteriorated ($\sum_{v,f} \tilde{\eta}_{vf}.\delta_{tvf}$). Moreover, a product unit disposal cost, SV , follows the multiple-breakpoint function defined by Eq. (2).

Eq. (4) represents the environmental goal, which is minimization of total GHG emission from the supply chain. It consists of GHG emitted by transportation, deterioration of on-hand inventories, and deterioration of on-the-way inventories, respectively.

Eq. (5) is related to minimization of the total variation in the labor level from one period to another. It consists of two terms, variation in the required level of logistics and transportation workers, respectively. This equation is considered as a social objective function. As mentioned, changes in labor levels from one period to another not only explicitly affect costs of systems (due to the costs of hiring, firing, etc), but also have implicit and negative effects on job satisfaction, well-being, and loyalty of personnel. Defining Z_2 and Z_3 along with Z_1 leads to an economic ordering policy, which is compatible with the two main criteria of sustainability, i.e. minimization of GHG emissions (an environmental index) and labor level variations (a social index).

Constraint (6) is the inventory balance equation. Since the on-hand inventories deteriorate at rate $\tilde{\theta}$, in Eq. (6), the initial inventory of period t is regarded as $(1-\tilde{\theta}).I_{(t-1)}$. Also, $\tilde{\beta}$ percent of the unfulfilled demand (shortage) in period $(t-1)$ is transferred to period t , which in Eq. (6) is regarded as part of that period's requirements. Constraint (7) implies that inventory and shortage levels of each period cannot take positive values concurrently. Since the ordering cost is incurred when the order quantity is positive, Constraint (8) is defined. Constraint (9) represents the equation for the on-the-way deteriorated inventories in each period. Constraint (10) means that order quantity in each period is the sum of non-perished products delivered by all transportation vehicles. Constraint (11) is defined to determine the number of required logistics workers in period t , HU_t . According to this constraint, the gross order quantity of each period, $\sum_{v,f} \delta_{tvf}$, is divided by HUM. The quotient is then rounded up to determine how many workers are needed to handle logistic activities (excluding transportation) at period t , i.e. HU_t . In this way, Constraint (11) explicitly and

other constraints, including decision variables, δ_{tvf} , implicitly affect the social criterion (Z_3).

Constraint (12) guarantees that the quantity transported by vehicles is less than or equal to vehicle capacity. Constraint (13) shows the number of used type- v vehicles is less than or equal to the available type- v vehicles. Constraints (14) and (15) define variable types.

5.2. Equivalent linear mathematical model

There are several nonlinear expressions in the model developed above. In this section, we develop an equivalent linear mathematical model by applying some linearization techniques to find global optimum solutions by the help of some optimization packages. As stated in Section 5.1., Constraint (7) implies that I_t and B_t cannot be positive values concurrently. Constraint (7) can be converted to its equivalent linear form by the following two constraints:

$$B_t \leq M.N_t \quad \forall t, \tag{16}$$

$$I_t \leq M.(1 - N_t) \quad \forall t, \tag{17}$$

where, in Eqs.(16) and (17), $N_t, t = 1, \dots, T$ are binary variables as follows:

$$N_t = \begin{cases} 1 & I_t = 0 \\ 0 & B_t = 0 \end{cases} \quad \forall t \tag{18}$$

Generally, an ordering cost (O) is incurred in a period if the order quantity at that period is positive, as in Constraint (8). The ordering cost at period t can be stated as linear expression, $O.V_t$, where V_t are binary variables and the following constraint holds:

$$\frac{V_t}{M} \leq Q_t \leq M.V_t. \tag{19}$$

In Constraint (19), the binary variables, $O.V_t$, are equal to 1 if $Q_t > 0$, and 0 otherwise:

$$V_t = \begin{cases} 1 & Q_t > 0 \\ 0 & Q_t = 0 \end{cases} \quad \forall t \tag{20}$$

The total sale in period t and S_t is as Eq. (21). In other words, the total sale is equal to the minimum amount of requirements ($D_t + \tilde{\beta}.B_{(t-1)}$) and inventories ($Q_t + (1 - \tilde{\theta}).I_{(t-1)}$) as follows:

$$S_t = \min \left\{ Q_t + (1 - \tilde{\theta}).I_{(t-1)}, \tilde{D}_t + \tilde{\beta}.B_{(t-1)} \right\} \\ = \begin{cases} Q_t + (1 - \tilde{\theta}).I_{(t-1)}, & \tilde{D}_t + \tilde{\beta}.B_{(t-1)} \geq Q_t \\ & + (1 - \tilde{\theta}).I_{(t-1)} \\ \tilde{D}_t + \tilde{\beta}.B_{(t-1)}, & \tilde{D}_t + \tilde{\beta}.B_{(t-1)} < Q_t \\ & + (1 - \tilde{\theta}).I_{(t-1)} \end{cases} \tag{21}$$

The linearization process of total sale is implemented in three steps.

- **Step 1:** At this step, we define binary variables, Y_t and non-negative variables Q'_t and Q''_t . By these variables, Eq. (21) is transformed into Eq. (22):

$$S_t = Q'_t + (1 - \tilde{\theta}) \cdot I_{(t-1)} \cdot Y_t + (\tilde{D}_t + \tilde{\beta} \cdot B_{(t-1)}) \cdot (1 - Y_t) \quad \forall t, \tag{22}$$

where the following constraints must be added to the main model:

$$Q'_t \leq (\tilde{D}_t + \tilde{\beta} \cdot B_{(t-1)} - (1 - \tilde{\theta}) \cdot I_{(t-1)}) \cdot Y_t \quad \forall t, \tag{23}$$

$$\begin{aligned} & (\tilde{D}_t + \tilde{\beta} \cdot B_{(t-1)} - (1 - \tilde{\theta}) \cdot I_{(t-1)}) \cdot (1 - Y_t) \\ & \leq Q''_t \leq M \cdot (1 - Y_t) \quad \forall t, \end{aligned} \tag{24}$$

$$Q'_t + Q''_t = Q_t \quad \forall t. \tag{25}$$

- **Step 2:** To transform the product terms $I_{(t-1)} \cdot Y_t$ and $B_{(t-1)} \cdot Y_t$ (in Eqs. (22)-(24)) into linear terms, two non-negative variables f_t and w_t are introduced, where $f_t = I_{(t-1)} \cdot Y_t$ and $w_t = B_{(t-1)} \cdot Y_t$. Thus, Eqs. (22)-(24) are replaced by Eqs. (26)-(28) as follows:

$$S_t = Q'_t + (1 - \tilde{\theta}) \cdot f_t + \tilde{D}_t \cdot (1 - Y_t) + \tilde{\beta} \cdot B_{(t-1)} - \tilde{\beta} \cdot w_t \quad \forall t, \tag{26}$$

$$Q'_t \leq \tilde{D}_t \cdot Y_t + \tilde{\beta} \cdot w_t - (1 - \tilde{\theta}) \cdot f_t \quad \forall t, \tag{27}$$

$$\begin{aligned} & (1 - Y_t) \cdot \tilde{D}_t + \tilde{\beta} \cdot B_{(t-1)} - \tilde{\beta} \cdot w_t - (1 - \tilde{\theta}) \\ & \cdot I_{(t-1)} + (1 - \tilde{\theta}) \cdot f_t \leq Q''_t \leq M \cdot (1 - Y_t) \quad \forall t. \end{aligned} \tag{28}$$

The non-linear equation $f_t = I_{(t-1)} \cdot Y_t$ can also be replaced by the following two linear equations:

$$-Y_t \cdot M \leq f_t \leq Y_t \cdot M \quad \forall t, \tag{29}$$

$$I_{(t-1)} - (1 - Y_t) \cdot M \leq f_t \leq I_{(t-1)} + (1 - Y_t) \cdot M \quad \forall t. \tag{30}$$

Equation $w_t = B_{(t-1)} \cdot Y_t$ is similarly substituted by linear Constraints (31) and (32):

$$-Y_t \cdot M \leq w_t \leq Y_t \cdot M \quad \forall n, \tag{31}$$

$$B_{(t-1)} - (1 - Y_t) \cdot M \leq w_t \leq B_{(t-1)} + (1 - Y_t) \cdot M \quad \forall t. \tag{32}$$

According to these two steps, the total sale at period t , S_t can be stated as a linear expression (Eq. (26)). In this way, some extra variables ($Y_t, Q'_t, Q''_t, f_t, w_t$)

and constraints (Eqs. (25)-(32)) are added into the main model.

The total revenue at period t is indicated by R_t . It is obtained by selling price (pr) times total sale (S_t), i.e. $R_t = pr \cdot S_t$. Thus, if the selling price of product (pr) is a constant parameter, the total revenue at period t ($pr \cdot S_t$) is linear. However, in our problem, the selling price of product (pr) is quantity-dependent following Eq. (1). Thus, the total revenue at period t is as follows:

$$R_t = pr \cdot S_t = \begin{cases} pr_1 \cdot S_t & SA_0 \leq S_t < SA_1 \\ pr_2 \cdot S_t & SA_1 \leq S_t < SA_2 \\ \dots & \dots \\ pr_m \cdot S_t & SA_{m-1} \leq S_t < SA_m \end{cases} \quad \forall t \tag{33}$$

where S_t is expressed in Eq. (26). The next step is therefore defined to develop the equivalent linear expression for the above multiple-breakpoint total revenue function.

- **Step 3:** To formulate Eq. (33) as a linear expression, we define binary variables, t_{tm} and non-negative variables, SL_{tm} . Then, Constraints (34)-(36) are added as follows:

$$SA_{m-1} \cdot t_{tk} \leq SL_{tm} \leq SA_m \cdot t_{tm} \quad \forall m, t, \tag{34}$$

$$S_t = \sum_m SL_{tm} \quad \forall t, \tag{35}$$

$$\sum_m t_{tm} = 1 \quad \forall t. \tag{36}$$

The total revenue at period t (R_t) can therefore be formulated as a linear expression, $R_t = \sum_m pr_m \cdot SL_{tm}$.

Another linearization process is related to disposal cost. As mentioned, the disposal cost of each unit of product follows a multiple-breakpoint function as stated in Eq. (2). The disposal cost can therefore become linear by using the technique applied in Step 3 of revenue linearization process. In this way, non-negative variables, IL_{tp} , and binary variables, α_{tp} , are defined, where $t \in \{1, \dots, T\}$ and $p \in \{1, \dots, P\}$. Then, the following constraints should be added to the model:

$$K_{p-1} \cdot \alpha_{tp} \leq \tilde{\theta} \cdot IL_{tp} \leq K_p \cdot \alpha_{tp} \quad \forall p, t, \tag{37}$$

$$I_t = \sum_p IL_{tp} \quad \forall t, \tag{38}$$

$$\sum_p \alpha_{tp} = 1 \quad \forall t. \tag{39}$$

In this way, the disposal cost of deteriorated on-hand inventories can be stated by the linear expres-

sion $\sum_t \sum_p SV_p \cdot \tilde{\theta} \cdot IL_{tp}$. In a similar way, disposal cost of on-the-way inventories is stated by linear expressions. λ_t represents on-the-way inventories deteriorated in period t , i.e. $\lambda_t = \sum_{v,f} \tilde{\eta} \cdot \delta_{tvf}$. By defining binary variables, α'_{tp} , non-negative variables, λL_{tp} , and Constraints (40)-(42), total disposal costs of on-the-way inventories can be stated as $\sum_t \sum_p SV_p \cdot \lambda L_{tp}$:

$$K_{p-1} \cdot \alpha'_{tp} \leq \lambda L_{tp} \leq K_p \cdot \alpha'_{tp} \quad \forall p, t, \quad (40)$$

$$\lambda_t = \sum_p \lambda L_{tp} \quad \forall t, \quad (41)$$

$$\sum_p \alpha'_{tp} = 1 \quad \forall t. \quad (42)$$

When an order is received by the retailer, non-deteriorated products are isolated from deteriorated ones. In this way, deteriorated on-the-way inventories are disposed at the beginning of the periods while disposing of deteriorated on-hand inventories is done at the end of each period. In other words, disposing of deteriorated on-the-way inventories and deteriorated on-hand products are carried out at the same time. This is why we separate the linearization procedure of these two processes' costs. With some minor modifications, the developed mathematical model can also be applicable when these two processes are done concurrently.

Finally, the last non-linear expression in the mathematical model developed in Section 5.1. is related to Z_3 (Eq. (5)) including absolute terms. The term $|HU_t - HU_{(t-1)}|$ could be converted to a linear one with the help of two non-negative auxiliary variables HU_t^+ and HU_t^- as follows:

$$|HU_t - HU_{(t-1)}| = HU_t^+ + HU_t^-, \quad (43)$$

s.t.

$$HU_t - HU_{(t-1)} = HU_t^+ - HU_t^-. \quad (44)$$

Similarly, the term $|\sum_f X_{tvf} - \sum_f X_{(t-1)vf}|$ is converted to a linear expression by defining two auxiliary variables $XT_{tv}^+ \geq 0$ and $XT_{tv}^- \geq 0$.

Consequently, the linear form of the developed model can be expressed as follows:

$$\begin{aligned} \text{Max } Z_1 = & \sum_{t,k} pr_k \cdot S_{tk} - \sum_{t>0} \left(O \cdot V_t + C \cdot \sum_{v,f} \delta_{tvf} \right. \\ & + h \cdot I_t + (1 - \tilde{\beta}) \cdot \pi \cdot B_t + \tilde{\beta} \cdot \gamma \cdot B_t \\ & + \sum_{v,f} (TA_{vf} \cdot d_f \cdot X_{tvf}) + \sum_p (SV_p \cdot \tilde{\theta} \cdot IL_{tp}) \\ & \left. + \sum_p (SV_p \cdot \lambda L_{tp}) + CH_t \cdot HU_t \right), \quad (45) \end{aligned}$$

$$\begin{aligned} \text{Min } Z_2 = & \sum_{t>0} \left(\sum_{v,f} (G_{vf} \cdot d_f \cdot X_{tvf}) \right. \\ & \left. + GD \cdot (\lambda_t + \tilde{\theta} \cdot I_t) \right), \quad (46) \end{aligned}$$

$$\begin{aligned} \text{Min } Z_3 = & \sum_t (HU_t^+ + HU_t^-) + \sum_{t,v} HT_v \\ & \cdot (XT_{tv}^+ + XT_{tv}^-), \quad (47) \end{aligned}$$

s.t.

$$Q_t + (1 - \tilde{\theta}) \cdot I_{(t-1)} - \tilde{D}_t - \tilde{\beta} \cdot B_{(t-1)} = I_t - B_t \quad \forall t, \quad (48)$$

$$B_t \leq M \cdot N_t \quad \forall t, \quad (49)$$

$$I_t \leq M \cdot (1 - N_t) \quad \forall t, \quad (50)$$

$$\frac{V_t}{M} \leq Q_t \leq M \cdot V_t \quad \forall t, \quad (51)$$

$$S_t = \sum_m SL_{tm} \quad \forall t, \quad (52)$$

$$SA_{m-1} \cdot t_{tm} \leq SL_{tm} \leq SA_m \cdot t_{tm} \quad \forall m, t, \quad (53)$$

$$\sum_m t_{tm} = 1 \quad \forall t, \quad (54)$$

$$\begin{aligned} S_t = & Q'_t + (1 - \tilde{\theta}) \cdot f_t + \tilde{D}_t \cdot (1 - Y_t) + \tilde{\beta} \cdot B_{(t-1)} \\ & - \tilde{\beta} \cdot w_t \quad \forall t, \quad (55) \end{aligned}$$

$$Q'_t \leq \tilde{D}_t \cdot Y_t + \tilde{\beta} \cdot w_t - (1 - \tilde{\theta}) \cdot f_t \quad \forall t, \quad (56)$$

$$\begin{aligned} (1 - Y_t) \cdot \tilde{D}_t + \tilde{\beta} \cdot B_{(t-1)} - \tilde{\beta} \cdot w_t - (1 - \tilde{\theta}) \cdot I_{(t-1)} \\ + (1 - \tilde{\theta}) \cdot f_t \leq Q''_t \leq M \cdot (1 - Y_t) \quad \forall t, \quad (57) \end{aligned}$$

$$-Y_t \cdot M \leq f_t \leq Y_t \cdot M \quad \forall t, \quad (58)$$

$$I_{(t-1)} - (1 - Y_t) \cdot M \leq f_t \leq I_{(t-1)} + (1 - Y_t) \cdot M \quad \forall t, \quad (59)$$

$$-Y_t \cdot M \leq w_t \leq Y_t \cdot M \quad \forall t, \quad (60)$$

$$B_{(t-1)} - (1 - Y_t) \cdot M \leq w_t \leq B_{(t-1)} + (1 - Y_t) \cdot M \quad \forall t, \quad (61)$$

$$Q'_t + Q''_t = Q_t \quad \forall t, \quad (62)$$

$$K_{p-1} \cdot \alpha_{tp} \leq \tilde{\theta} \cdot IL_{tp} \leq K_p \cdot \alpha_{tp} \quad \forall p, t, \quad (63)$$

$$I_t = \sum_p IL_{tp} \quad \forall t, \tag{64}$$

$$\sum_p \alpha_{tp} = 1 \quad \forall t, \tag{65}$$

$$K_{p-1} \cdot \alpha'_{tp} \leq \lambda L_{tp} \leq K_p \cdot \alpha'_{tp} \quad \forall p, t, \tag{66}$$

$$\lambda_t = \sum_p \lambda L_{tp} \quad \forall t, \tag{67}$$

$$\sum_p \alpha'_{tp} = 1 \quad \forall t, \tag{68}$$

$$\lambda_t = \sum_{v,f} \tilde{\eta} \cdot \delta_{tvf} \quad \forall t, \tag{69}$$

$$HU_t - HU_{(t-1)} = HU_t^+ - HU_t^- \quad \forall t, \tag{70}$$

$$\sum_f X_{tvf} - \sum_f X_{(t-1)vf} = XT_{tv}^+ - XT_{tv}^- \quad \forall t, v, \tag{71}$$

$$Q_t = \sum_{v,f} (1 - \tilde{\eta}_{vf}) \cdot \delta_{tvf} \quad \forall t, \tag{72}$$

$$(HU_t - 1) \leq \frac{\sum_{v,f} \delta_{tvf}}{HUM} \leq HU_t \quad \forall t, \tag{73}$$

$$Q_{tvf} \leq CAP_v \cdot X_{tvf} \quad \forall t, f, v, \tag{74}$$

$$\sum_f X_{tvf} \leq MAXT_v \quad \forall v, t, \tag{75}$$

$$X_{tvf}, HU_t, HU_t^+, HU_t^-, XT_{tv}^+, HT_{tv}^- \geq 0, \text{ integer} \tag{76}$$

$$\forall t, v, f,$$

$$N_t, V_t, Y_t, t_{tm}, \alpha_{tp}, \alpha'_{tp} \in \{0, 1\} \quad \forall t, m, p, \tag{77}$$

$$Q_t, Q'_t, Q''_t, \delta_{tvf}, \lambda_t, \lambda L_{tp}, I_t, IL_{tp}, B_t, S_t, SL_{tk}, \tag{78}$$

$$f_t, w_t \geq 0 \quad \forall t, v, f, m, p,$$

6. Solution approach

A possibilistic programming approach is taken to solve the mixed-integer linear model with fuzzy parameters developed in the previous sections. To develop the equivalent crisp model, we use the Jimenez et al. [44] method. A brief explanation of this method follows and interested readers are referred to Jimenez et al. [44] for more details.

Assume that $\tilde{a} = (a^p, a^m, a^0)$ shows a triangular fuzzy number. Then, the expected value ($E(\tilde{a})$) and the expected interval ($I(\tilde{a})$) of \tilde{a} are respectively defined as follows:

$$E(\tilde{a}) = \frac{E_1^a + E_2^a}{2} = \frac{a^p + 2a^m + a^0}{4}, \tag{79}$$

$$I(\tilde{a}) = [E_1^a, E_2^a] = \left[\frac{1}{2}(a^p + a^m), \frac{1}{2}(a^m + a^0) \right]. \tag{80}$$

Additionally, the mathematical model developed in the previous section can be presented by the following parametric multi-objective linear mathematical programming model, in which i) There are H different objective functions, Z_1, \dots, Z_H , and ii) All parameters are considered as triangular fuzzy numbers:

$$\begin{aligned} \text{Min} \quad & z_1 = \tilde{c}_1^t x \\ & \dots \\ \text{Min} \quad & Z_H = \tilde{c}_H^t x \\ \text{s.t.} \quad & \tilde{a}_i x \geq \tilde{b}_i, \quad i = 1, \dots, l, \\ & \tilde{a}_i x = \tilde{b}_i \quad i = l + 1, \dots, l \\ & x \geq 0. \end{aligned} \tag{81}$$

Based on Jimenez et al. [44] and the definition of the expected value and the expected interval of triangular fuzzy numbers presented in Eqs. (79) and (80), the equivalent crisp-parametric model of the above model (Eq. (81)) may be written as follows:

$$\begin{aligned} \text{Min} \quad & z_1 = E(\tilde{c}_1)^t \cdot x \\ & \dots \\ \text{Min} \quad & Z_H = E(\tilde{c}_H)^t \cdot x \\ \text{s.t.} \quad & [(1 - \alpha)E_2^{a_i} + \alpha E_1^{a_i x}] = x \geq \alpha E_2^{b_i} + (1 - \alpha)E_1^{b_i} \\ & \quad i = 1, \dots, l, \\ & \left[\left(1 - \frac{\alpha}{2}\right) E_2^{a_i} + \frac{\alpha}{2} E_1^{a_i x} \right] x \geq \frac{\alpha}{2} E_2^{b_i} + \left(1 - \frac{\alpha}{2}\right) E_1^{b_i} \\ & \quad i = l + 1, \dots, m \\ & \left[\left(\frac{\alpha}{2}\right) E_2^{a_i} + \left(1 - \frac{\alpha}{2}\right) E_1^{a_i x} \right] x \geq \left(1 - \frac{\alpha}{2}\right) E_2^{b_i} + \frac{\alpha}{2} E_1^{b_i} \\ & \quad i = l + 1, \dots, m \\ & x \geq 0, \end{aligned} \tag{82}$$

where α shows feasibility degree of a solution. Finally, based on Selim and Ozkarahan [45], the auxiliary crisp multi-objective Mixed Integer Linear Programming (MILP) model is converted into an equivalent single-objective MILP model using the following new auxiliary crisp formulation:

Table 3. Transportation vehicle’s data.

V	CAP _v	MAXT _v	HT _v	TA _{v,f} , f = 1, 2	Path 1		Path 2	
					ñ _{v1}	G _{v1}	ñ _{v2}	G _{v2}
1 (Small)	500	10	1	15	(0.06, 0.08, 0.1)	75	(0.03, 0.04, 0.05)	30
2 (Medium)	900	10	1	18	(0.06, 0.08, 0.1)	115	(0.03, 0.04, 0.05)	60
3 (Large)	1200	10	1	21	(0.06, 0.08, 0.1)	123	(0.03, 0.04, 0.05)	75

$$\text{Max } \chi \cdot \lambda_0 + (1 - \chi) \sum_h w_h \mu_h(x), \tag{83}$$

s.t.

$$\lambda_0 \leq \mu_h(x) \quad h \in \{1, \dots, H\}$$

$$x \in F(x), \lambda_0 \text{ and } \chi \in [0, 1],$$

where w_h indicates relative importance of the h th objective function; $F(x)$ denotes feasible region (area) involving crisp constraints in model (82).

Finally, by specifying the minimum and maximum amounts of each objective function separately, the linear membership function for each objective is defined as follows:

$$\mu_h(x) = \begin{cases} 1 & Z_h > Z_h^{\max} \\ \frac{Z_h - Z_h^{\min}}{Z_h^{\max} - Z_h^{\min}} & Z_h^{\min} \leq Z_h \leq Z_h^{\max} \\ 0 & Z_h < Z_h^{\min} \end{cases} \quad h \in \{1, \dots, H\} \tag{84}$$

In Eq. (84), Z_h^{\min} and Z_h^{\max} show the minimum and maximum values of Z_h , respectively.

7. Numerical analysis

In the following, we apply the proposed model to a supply chain with a retailer, a fresh produce center in Tehran, Iran, and its supplier. A centralized decision-making process is applied in this supply chain. The planning horizon consists of three periods. Different levels of demand (optimistic, most likely, and pessimistic) at the first, second, and third periods are predicted as (12000, 13000, 14000), (9000, 10000, 11000), and (1600, 1700, 1800), respectively.

The ordering and purchasing costs are estimated as $A = \text{€}50000/\text{ordering}$ and $C = \text{€}50/\text{unit}$, respectively. On average, one worker is required for supplying and purchasing 10 units of products, i.e. $HUM = 10$. Since the cost of hiring a worker is tiny in comparison with other costs, without loss of generality, we consider $CH_t = 0$. The selling price, pr , is as follows:

$$pr = \begin{cases} 300 & 0 \leq S_t < 5000 \\ 280 & 5000 \leq S_t < 10000 \\ 250 & 10000 \leq S_t \end{cases} \tag{85}$$

The product deterioration rate is estimated by $\tilde{\theta} = (0.03, 0.05, 0.07)$. GHG level produced by a unit of deteriorated product is estimated as $GD = 60$ gr/unit. The retailer’s initial inventory and initial shortage levels are $I_0 = 50$ and $B_0 = 0$ units, respectively.

There are two routes (paths) between supplier and retailer. The first route, called the “desert path”, passes through a hot and dry zone while the second route passes through a forest area. The second route is called the “green path”, since a significant portion of GHG emissions produced by the transportation vehicles is refined and dissipated by the plants. However, the green path is longer and more expensive than the desert one. The length of the desert path is 15 km while the green path is about 30% longer (20 km).

Three types of vehicles (small, medium, and large) are available for transferring orders. Information on the transportation vehicle is summarized in Table 3.

According to Table 3, due to climate conditions, deterioration rate of products is higher in Path 1 than in Path 2.

In each period, based on total supply (quantity ordered as well as uncertain remaining inventory from the previous period) and requirements (uncertain back-ordered demands as well as new uncertain demands), three situations may take place:

- (i) Requirement is less than supply, i.e. the inventory level is positive and shortage is zero at the end of the period. In this case, $\tilde{\theta}$ percent of the remaining inventory is deteriorated with a cost of SV:

$$SV = \begin{cases} 30 & 0 \leq \text{disposal quantity} < 100 \\ 25 & 100 \leq \text{disposal quantity} < 200 \\ 10 & 200 \leq \text{disposal quantity} \end{cases} \tag{86}$$

The rest of the inventories are stocked, up to the next period, with a cost of $h = 5\text{€}/\text{unit}$;

- (ii) Requirement is more than supply, which implies that inventory and shortage levels are zero and positive, respectively, at the end of the period. In this case, $\tilde{\beta} = (0.03, 0.05, 0.07)$ of unfulfilled demands is backordered and transferred to the next period with a cost of $\gamma = 10\text{€}/\text{unit}$. The rest is regarded as lost sales with a cost of $\pi = 100\text{€}/\text{unit}$;

Table 4. Optimal decision variables and objective functions.

w_1	w_2	w_3	Q_1	Q_2	Q_3	X_1	X_2	X_3	Z_1	Z_2	Z_3
1	0	0	12950	11771	0	[0,3,9][0,0,0]	[0,3,8][0,0,0]	[0,0,0][0,0,0]	5144276	107830	2721
0.6	0.2	0.2	9950	9970	1719	[0,0,0][4,0,7]	[0,0,0][4,0,7]	[0,0,0][0,1,1]	4504656	82704	1925

Table 5. The objective functions' components.

	Z_1					Z_2			Z_3			
	R	BC	LC	HC	OC	PC	DC	TC	$GHG-D$	$GHG-T$	HT	HS
$w_1=1, w_2=w_3=0$	6560000	0	0	8856	100000	1287600	12293	6975	66115	41715	24	2697
$w_1=0.6, w_2=w_3=0.2$	6104300	1590	302100	50	150000	1127100	9744.4	9060	54204	28500	30	1898

Note: R : Total revenue; BC : Backorder Cost; LC : Lost-sale Cost; HC : Holding Cost; OC : Ordering Cost;

PC : Procurement Cost; DC : Disposal Cost; TC : Expected transportation cost;

$GHG-D$: GHG emission produced by deterioration; $GHG-T$: GHG emission produced by transportation;

HT : Variations in required labor for transportation; HS : Variations in required labor for supplying product;

- (iii) Requirement is equal to supply, which means no shortage or inventory exists at the end of the period.

All computations were run applying the CPLEX algorithm accessed via IBM ILOG CPLEX 12.2 on a PC Core (TM) i5 -2.3 GHz and 4.00 GB RAM under Windows 7 Home Premium.

In Table 4, the optimal value of the objective function is reported for two cases: i) first, the model is solved merely by considering the economic aspect, i.e. $w_1 = 1$ and $w_2 = w_3 = 0$; ii) then, by changing the relative weights ($w_1 = 0.6$, $w_2 = w_3 = 0.2$), the optimal values of decision variables are obtained by taking into account economic (Z_1), environmental (Z_2), and social (Z_3) aspects. The optimal values of the objective function components are reported in Table 5 for these two cases.

In Table 4, the optimal configuration of the vehicles in each period is reported as a symbol consisting of 2 vectors, each one showing the number of vehicles of each type used in each path. For example, when $w_1 = 1$, $w_2 = w_3 = 0$, $X_1^* = [0 \ 3 \ 9] [0 \ 0 \ 0]$ denotes that in the first period, three vehicles of type 2 and nine vehicles of type 3 are used in Path 1 (desert path) while no vehicle is used in Path 2 (green path).

As Table 4 shows, when $w_1 = 1$ and $w_2 = w_3 = 0$, the highest value for Z_1^* is 5,144,300. Whereas the worst values for GHGs emissions (Z_2^*) and labor variations (Z_3^*) are obtained in this state.

When the Decision Maker (DM) is concerned with environmental and social criteria as much as costs ($w_1 = 0.6$, and $w_2 = w_3 = 0.2$), the optimal values of the objective functions and decision variables are considerably modified. As Table 4 shows, by considering Z_2 and Z_3 in addition to Z_1 (an SSC), the system loses a part of the profit in comparison with a state that only regards the economic objective (an

economic supply chain). According to Table 4, the environmental and social objectives are improved by about 23.3% and 29.25%, respectively, by losing about 12.4% of total profit.

Considering sustainability criteria, optimal inventory and transportation policy and transportation paths are changed. As well, when the DM switches from an economic supply chain to a sustainable one, optimal values of order quantities are more homogeneous through the planning horizon. Some reasons for this event are i) maintaining variations in the required labor as minimum as possible, and ii) reducing GHG emission as well as costs related to the deterioration process. Values of disposal costs and their related GHGs confirm this statement in Table 5.

8. Sensitivity analysis

In this section, a sensitivity analysis is done regarding the weight (importance) of the objective function. For this purpose, the numerical analysis is done in three stages:

- i) Just economic and environmental criteria (Z_1 and Z_2) are considered;
- ii) Just economic and social criteria (Z_1 and Z_3) are considered; and
- iii) All economic, environmental, and social criteria (Z_1 , Z_2 and Z_3) are considered.

In the first step, we take into account just economic and environmental criteria (a green supply chain). Thus, $w_3 = 0$ and $w_2 = 1 - w_1$. The obtained results are reported in Table 6 and the Pareto solutions are presented in Figure 2.

According to Table 6 and Figure 2, whenever w_1 decreases (the weight of GHG criteria ($1 - w_1$) increases), lost profit and GHG reduction percentages

Table 6. Optimal decision variables and objective functions considering economic and environmental criteria, $w_2 = 1 - w_1$.

w_1	Q_1	Q_2	Q_3	X_1	X_2	X_3	z_1	z_2	Lost profit (%)	GHG reduction (%)
1	12950	11771	0	[0,3,9][0,0,0]	[0,3,8][0,0,0]	[0,0,0][0,0,0]	5144276	107830	–	–
0.9	12950	11789	0	[0,0,0][4,1,9]	[0,0,0][8,0,7]	[0,0,0][0,0,0]	5139400	98655	0.1	8.5
0.8	12950	10071	1632	[0,0,0][3,0,10]	[0,0,0][9,0,5]	[0,0,0][1,0,1]	5104600	93651	0.8	13.1
0.7	12950	10071	1632	[0,0,0][3,0,10]	[0,0,0][9,0,5]	[0,0,0][1,0,1]	5104600	93651	0.8	13.1
0.6	12864	10000	1632	[0,0,0][10,0,7]	[0,0,0][9,0,5]	[0,0,0][1,0,1]	5055400	92760	1.7	14.0
0.5	9792	9984	1632	[0,0,0][6,0,6]	[0,0,0][4,0,7]	[0,0,0][1,0,1]	4432300	81120	13.8	24.8
0.1-0.4	0	0	0	–	–	–	-2451800	0	–	–

Table 7. Optimal decision variables and objective functions considering economic and social criteria, $w_3 = 1 - w_1$.

w_1	Q_1	Q_2	Q_3	X_1	X_2	X_3	z_1	z_2	Lost profit (%)	Reduction in labor variations (%)
1	12950	11771	0	[0,3,9][0,0,0]	[0,3,8][0,0,0]	[0,0,0][0,0,0]	5144276	2721	—	—
0.9	12950	10000	1700	[0,3,9][0,0,0]	[0,1,8][0,0,0]	[0,1,8][0,0,0]	5106600	2535	0.7	6.8
0.8	9950	10000	9587	[0,3,9][0,0,0]	[0,3,9][0,0,0]	[0,3,9][0,0,0]	4626400	1667	10.1	38.7
0.7	9950	9990	9568	[0,1,8][0,0,0]	[0,1,8][0,0,0]	[0,1,8][0,0,0]	4036100	1050	21.5	61.4
0.6	9950	9990	9568	[0,1,8][0,0,0]	[0,1,8][0,0,0]	[0,1,8][0,0,0]	4036100	1050	21.5	61.4
0.5	9950	9950	9534	[0,1,8][0,0,0]	[0,1,8][0,0,0]	[0,1,8][0,0,0]	4025900	1046	21.7	61.6
0.4	9950	9950	9534	[0,1,8][0,0,0]	[0,1,8][0,0,0]	[0,1,8][0,0,0]	4025900	1046	21.7	61.6
0.3	2121	2121	2120	[0,0,2][0,0,0]	[0,0,2][0,0,0]	[0,0,2][0,0,0]	-400810	0223	147.7	91.8
0.1-0.2	0	0	0	—	—	—	-2451800	0	—	—

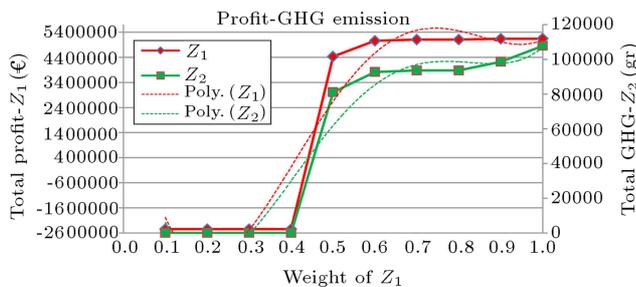


Figure 2. Optimal total profit against the optimal GHG emissions.

increase. In this way, when the importance factor (weight) of the green criteria is more than 0.5, purchasing is not sound and the supply chain has to be brought to a close. However, in some cases, an acceptable reduction in GHGs emissions is reachable with just a minor reduction in total profit. For example, when $w_1 = 0.7$ and $w_2 = 0.3$, about 13% GHG reduction can be obtained with less than 1% reduction in total profit. Besides, as Table 6 shows, when DM is concerned with the environmental criterion, the “green path” is the preferable one even though it is longer and more costly than the other path.

Table 7 presents optimal policies with attention to the economic and social criteria and disregarding the environmental aspect. Thus, $w_2 = 0$ and $w_3 = 1 - w_1$. Here, green criteria are not concerned ($w_2 = 0$). In all cases, Path 1 (desert path) is therefore the optimal path because it is shorter and more cost-effective.

Moreover, in some periods, an extra cost may be incurred for holding extra equipment whenever variations of required labors are important. For example, when $w_1 = 0.9$ ($w_3 = 0.1$), the optimal values of order quantities are determined as $Q_1 = 12950$, $Q_2 = 10000$, and $Q_3 = 1700$. However, at $Q_3 = 1700$, the optimal transportation vehicles are more than the required ones in the third period (a type-2 vehicle (capacity: 900) and eight type-3 vehicles (capacity: 1200)). In fact, to make variations of labors as low as possible, the supply chain is forced to have extra transportation vehicles in period 3, considering required labors in the first and second periods.

In addition, since the capacity of vehicle type-3 is more than the others, the system prefers to use vehicle type-3 more as the weight of Z_3 increases. In fact, by having high-capacity vehicles, the number of required vehicles for transferring order quantities

Table 8. Optimal decision variables and objective functions with economic, environmental, and social criteria.

w_1	w_2	w_3	Q_1	Q_2	Q_3	X_1	X_2	X_3	z_1	z_2	z_3
1	0	0	12950	11771	0	[0,3,9][0,0,0]	[0,3,8][0,0,0]	[0,0,0][0,0,0]	5144276	107830	2721
0.9	0.05	0.05	12950	10000	1700	[0,0,0][0,3,10]	[0,0,0][2,0,8]	[0,0,0][2,1,0]	5104400	94080	2545
0.8	0.1	0.1	12950	10000	1700	[0,0,0][0,3,10]	[0,0,0][2,0,8]	[0,0,0][2,1,0]	5104400	94080	2545
0.7	0.15	0.15	9950	9984	1708	[0,0,0][4,0,7]	[0,0,0][4,0,7]	[0,0,0][4,0,0]	4508400	82380	1919
0.6	0.2	0.2	9950	9970	1719	[0,0,0][4,0,7]	[0,0,0][4,0,7]	[0,0,0][0,1,1]	4504656	82704	1928
0.5	0.25	0.25	4896	4896	1968	[0,0,0][3,0,3]	[0,0,0][3,0,3]	[0,0,0][0,1,1]	1474800	44700	826
0.4	0.3	0.3	2112	2112	2112	[0,0,0][2,0,1]	[0,0,0][2,0,1]	[0,0,0][2,0,1]	-412650	23940	223
1/3	1/3	1/3	0	0	0	[0,0,0][0,0,0]	[0,0,0][0,0,0]	[0,0,0][0,0,0]	-2451800	0	0

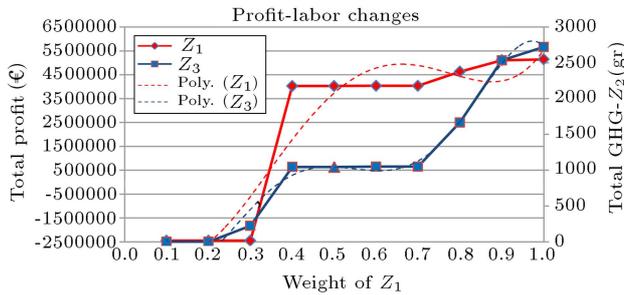


Figure 3. Optimal total profit against the optimal labor variations.

in different periods with various values will decrease. In other words, a high-capacity vehicle is able to transfer high and low quantities in different periods. Consequently, variations of the required labor for transportation will decrease through the planning horizon. Pareto solutions regarding Z_1 and Z_3 are presented in Figure 3.

Finally, Table 8 shows the optimal values of decision variables by considering all three objective functions. As this table shows, if DMs put very high values to social and environmental criteria, the supply chain loses its profitability. However, managers can play a positive role in improving social and environmental indices with just a minor cost (or lost profit).

For example, if the managers set $w_1 = 0.9$, $w_2 = 0.05$, and $w_3 = 0.05$, with less than 1% reduction in total profit, 12.8% and 6.5% improvements will be obtained regarding environmental and social criteria, respectively. This lost profit will be compensated in the medium- and long-term horizons by higher satisfaction, motivation, and, consequently, efficiency of workers. In other words, when the workers' sense of belonging and loyalty to their work rise (w_3 increases), their creativity and efficiency consequently improve. Finally, with fewer employees and, thus, fewer costs, goals and mission of the organization can be accomplished.

9. Conclusion

Deterioration of products is a major concern in SCM, since most products decrease in quality or value during

their life cycle. Deterioration is a non-linear function made up of many factors such as transportation types. The distinct feature of this research is that it is based on numerous characteristics of real deteriorating products and simultaneously considers all 3 sustainability dimensions in deteriorating products SCM.

This paper considered a centralized forward supply chain for a deteriorating product with various transportation options. Some variables such as the end-customer demand, the partial backordered ratio, and the deterioration rate were assumed to be uncertain. The two sources of deterioration were assumed to be: i) deterioration of in-stock inventories, and ii) deterioration of in-transit products, influenced by both transportation vehicles and transportation paths/modes. The vehicle types (or paths) had a considerable influence on transportation cost of each product, amount of GHG emission, and deterioration rate of product. A possibilistic mathematical model was developed to determine the optimal replenishment policy, transportation routes, and type of vehicles. It was solved after linearization of various expressions and constraints. The final solutions were illustrated using a fresh produce center in Tehran, Iran. The results show that DMs can manage green and social issues with a minor reduction in profits. Thus, managers may use what-if simulation to see the effects of higher economic and social values of their profitability.

The proposed model is certainly not inclusive and final, and further research is needed in the following respects:

- i) Considering dependency of path and vehicles to the lead-time;
- ii) Considering the accident risk related to features of vehicles and paths;
- iii) Expanding the proposed model by considering more detailed reverse logistic processes; and
- iv) Including multiple suppliers and multiple products.

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