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Multi-objective multi-product sustainable newsvendor management in an emerging economy: Evidence and applications

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ABSTRACT

The idea of a sustainable newsvendor problem has been considered by some researchers recently; nonetheless, an inclusive multi-objective model including all sustainability pillars with a multi-product supply chain has not been designed yet. In this paper, the newsvendor model is developed considering all sustainability criteria to study a two-stage procurement system. The classic newsvendor model of optimizing supplier-retailer payoff is considered in this research to illustrate the economic perspective of sustainability. Moreover, other objectives are formulated to model the social and environmental pillars of sustainability. These objectives minimize the environmental effects of the standard newsvendor problem regarding the malicious environmental effects of unrecyclable unsold products. To solve the formulated model a compromise programming approach is hybridized with Lagrange relaxation and sub-gradient optimization for the proposed model. For more clarification, a real-world case study from the Fast-moving consumer goods (FMCG) industry with real data has been employed alongside sensitivity analysis. Moreover, to evaluate the efficiency of the proposed solving approach, the Genetic Algorithm (GA) and Simulated Annealing (SA) algorithm were also designed and their parameters were tuned using the Taguchi method. Comparing the obtained results with the classical newsvendor model, the single economic objective loses at least 0.76% and at most 14.1% of its achievements by a trade-off with sustainable criteria. Furthermore, results indicated that both in terms of optimality and solution time, the proposed method has an extraordinary performance compared to GA and SA.

1. Introduction

The newsvendor problem is one of the well-known problems in the field of inventory control (Letkowski, 2018). The classic problem deals with the relation between a central warehouse (supplier) and a retailer who desires to determine his/her optimal ordering policy in a way that the sum of procurement costs being minimized (Hua et al., 2020). The formal formation of the problem dates back to the works of Edgeworth (1888) while the "newsboy" term first time was introduced by Morse and Kimball (1951). The standard form of newsvendor problem considered only a single type of inventory item in a single period while its later expansions considered multiple inventory items (Wu et al., 2020). A detailed review of newsvendor problem studies is given in the next section of the paper. Many supply systems around the world follow a similar structure as described in the newsvendor problem. Consider a central warehouse of a manufacturer that responds to the demands from several regional warehouses that directly meet the consumer's demand (Mu et al., 2019). This structure is illustrated in Fig. 1.

This type of procurement system is observed in different industries. However, one of the limitations of the standard model is that it purely focuses on financial analysis (Hu et al., 2018). The main global challenge of industries is to consider sustainability considerations in their decision-making processes (Tost et al., 2018). Sustainable development is a worldwide responsibility of industries that must be considered by planners and decision-makers (Baumgartner and Rauter, 2017). Sustainability refers to the responsibility of organizations regarding the environment and society (Rodriguez et al., 2018). The necessity of sustainable development roots back to understating human actions effect on the natural environment (Klarin, 2018). Serious environmental crises due to globalization and modernization raised the importance of

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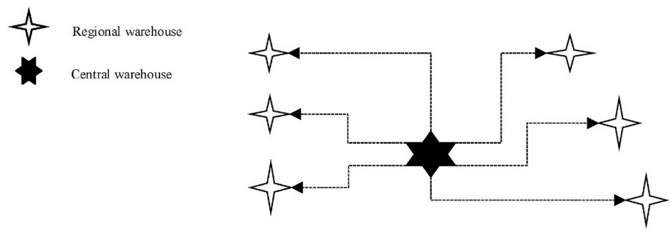


Fig. 1. The central – regional warehouse system of a manufacturer (source: authors).

sustainability consideration in policymaking. This importance is intensified by the amount of pollution being raised due to either manufacturing or recycling of products. (Tian et al., 2018; Wang et al., 2020). Sustainable development includes three pillars of economic, social, and environmental sustainability (Purvis et al., 2019). Beyond its theoretical and conceptual discussions, these considerations made a fundamental change in the analytical models and governmental regulatory activities regarding how to control sustainability-related issues. Different frameworks are proposed to visualize a sustainable development concept (e.g. Teuteberg and Wittstruck, 2010; Zhu and Hua, 2017). Moreover, the United Nations agreed on 17 goals for sustainable development (United Nations, 2015).

Beyond its theoretical and practical discussions, the main idea is that while some organizational participants believe that sustainability is less important than financial performance (Bento et al., 2019), some other drivers have reinforced organizations to concern it in their decisions (Lozano and von Haartman, 2018). Inventory management and newsvendor problem have gained a lot of consideration due to their effective role towards sustainability and play an important role in the adoption and implementation of sustainability based on the triple bottom line (TBL) model (Agrawal and Singh, 2019). The impact of inventory management optimization of perishable and non-perishable products and related inventory and processing costs has been considered by many scholars recently (e.g. Tiwari et al., 2018; Paam et al., 2019) indicating the importance of this issue. Note that, one of the limitations of the classic newsvendor model is considering only economic factors without employing social and environmental aspects within their models.

The idea of a sustainable newsvendor problem has been considered by some scholars recently (e.g. Tsao et al., 2017; Rogetzer et al., 2019). Nonetheless, to the best knowledge of the authors an inclusive multi-objective model including TBL pillars with a multi-product supply chain has not been designed yet. The main contribution of the proposed method is to consider sustainability concerns in the context of a system being analyzed through the newsvendor problem structure. According to the studied literature, this matter has not been considered in previous research works. In other words, the classic newsvendor model is profit maximization based without any consideration toward sustainability issues. In fact, the classic model only formulates an objective function of maximizing the profit function without any attention to non-economic factors. However, the necessity of sustainability makes it impossible to optimize the newsvendor problem in an unsustainable model. In this regard and according to the non-commensurable and contradictory nature of profit and sustainability objectives, in this research, a multi-objective model is formulated to simultaneously optimize the profit and sustainable dimensions of the considered problem. To solve the multi-objective formulated model, first, the model is transformed into a single-objective model using the idea of compromise programming (Ringuest, 1992). Then, a Lagrange relaxation sub-gradient optimization algorithm has been designed and developed by the authors. The main motivation of proposing the current paper is justified considering the lack of a unique study to examine the multi-product, multi-objective newsvendor model when different products behaved differently according to distinct statistical distribution by bringing up several sustainability pillars.

The remainder of the paper is organized as follows. The framework of the standard newsvendor problem along with its literature is reviewed in section 2. Then, the proposed formulation is described in section 3. The solving approach of the model is then introduced in section 4. A real-world case study is represented in section 5 and finally, the paper is concluded in section 6.

2. Newsvendor problem

The classic Newsvendor or newsboy model is a single-period inventory management system. The basic mathematical problem was presented in 1888 where Edgeworth used the central limit theorem (CLT) from statistics to determine the optimal cash reserves to satisfy random withdrawals from depositors. However, the well-known classical formulation originated from Arrow et al. (1951). Moreover, the newsvendor model is pertinent to the capacity and revenue management problems due to the single-period irreversible decisions and the stochastic environment (Guo et al., 2019; Khuoja et al., 2020). In this regard, a specific perishable good is sold during one season and the order quantity requires to be determined before the market debut without knowing the demand in uncertain situations. Considered products are a single period due they have a restricted consumption lifetime. Assume that optimizing the inventory level for a perishable product is targeted. In this regard, the demand is stochastic or probabilistic (Cachon, 2003). Note that the demand is a random variable being independent of price and opted from a continuous distribution with determined probability density functions (PDF = f(.)) and cumulative density function (CDF=F (.)). Since demand is a random variable; accordingly, the profit behaves randomly, and alternates based on the ordering quantity. Consider (D) as the demand variable and (Q) as the order quantity and (p,c) as selling price and cost, respectively; hence, the profit is measured as follows.

$$profit = \begin{Bmatrix} pD - cQ; \ D \le Q \\ pQ - cQ; \ D > Q \end{Bmatrix} \tag{1}$$

The final object of this model is to optimize the ordering quantity (Q*) when maximizes the expected profit. This optimal value for a different distribution of demand leads to different results. For three well-known distribution functions including Normal (N), Lognormal (L), and Uniform (U), the optimal value of order quantity results as follows (Zhang et al., 2012). Note that the Z^{-1} shows the inverse Z-score of the standard normal distribution.

$$U\ Q^* = D_{min} + \left[(D_{max} - D_{min}) \times \frac{p-c}{p} \right] \tag{2}$$

$$N\ Q^* = \mu + \left[\sigma \times Z^{-1}\left(\frac{p-c}{p}\right) \right]$$

$$L\ Q^* = \mu \times e^{Z^{-1}\left(\frac{p-c}{p}\right)}$$

The abovementioned newsvendor model is based on maximizing profit function; nonetheless, the second approach considers a cost-based optimization inventory level. In this regard, in case the perishable product demand exceeds the supplied quantity, an opportunity or underage cost (C_u) of (D − Q)*(p −c) represents lost revenue due to a shortage. On the contrary, in case the demand is equal to or less than the provided quantity, an overage cost (Co) of (Q − D)*c occurs due to the product is perishable. Accordingly, the newsvendor problem was presented and analyzed as minimizing the expectation of the sum of the opportunity and the overage cost (Fu et al., 2017). The optimum order quantity for this situation is as follows.

$$Q = F^{-1}\left(\frac{C_U}{C_U + C_O}\right) \tag{3}$$

Since the original development of the newsvendor model, some

Table 1
An overview of related approaches toward the newsvendor problem since 2010.

Scholar	Year	product		Demand							Pillars as objects			Validation			Uncertainty		Developed Algorithm	Considered Variables	
		S	M	N	L	E/ P/ B	U	T	R	G	ECN	ENV	SCL	A numerical example and sensitivity analysis	Simulation and DoE	Rea l world Case Study	Demand	Risk/ Price/ Supply		Order/ Inventory	Pricing
Sevi	2010	*							*		*			*			*	*	-	*	
Reimann	2011		*	*							*			*			*	*	-	*	*
Choi & Chiu	2012	*		*							*					*	*		-	*	
Zhang	2013		*							*	*			*	*		*		multi-tier binary	*	
Wu et al.	2014	*							*		*			*			*	*	-	*	*
Wang et al.	2015	*		*	*	*	*				*			*				*	-	*	*
Zhang & Yang	2016		*						*		*			*			*		Weak aggregating	*	
Chen et al.	2017	*		*							*			*			*		-		*
Arikan & Fichtinger	2017	*					*				*			*			*	*	-	*	
Vipin & Amit	2017	*					*				*			*			*	*	-	*	*
Fu et al.	2017		*	*							*			*			*		-		*
Tsao et al.	2017	*					*				*	*	*	*		*	*		-	*	*
Hu et al.	2018	*		*							*			*			*		-		*
Herrero & Gursoy	2018	*					*				*			*			*	*	-	*	*
Mitra	2018	*							*		*			*			*		-	*	*
Kyparisis & Koulamas	2018	*								*	*			*			*		-	*	*
Mohammadivojdana & Geunes	2018	*							*		*			*			*		heuristic	*	
Guler et al.	2018		*	*							*			*		*	*		-	*	
Murarkaa et al.	2019		*						*		*			*	*		*	*	cut generation	*	
Guo et al.	2019	*		*							*			*		*	*		-	*	
Huber et al.	2019	*		*							*			*		*	*		-	*	
Alavifard et al.	2019	*							*		*			*			*		-	*	
Rogetzer et al.	2019	*		*	*	*					*	*		*			*	*	-	*	
Ma	2019	*							*		*			*			*		-	*	*
Schulte & Sachs	2020	*				*					*		*	*			*		-	*	*
Herrero & Gursoy	2020	*		*			*	*			*		*	*			*	*	-		*
Proposed research	2021		*	*		*	*				*	*	*	*		*	*		Lagrange relaxation sub-gradient	*	

(S), single product; (M), Multi-product; (N), normal distribution; (L), lognormal or logistic distribution; (E/P/B), exponential or Beta or Poisson distribution; (U), uniform distribution; (R), Random or stochastic; (G), any continuous demand; (T), Triangular; (ECN), economic pillar; (ENV), environmental pillar; (SCL), social pillar.

improvements were designed for optimizing price as well as order quantity. These works focused on the price-setting newsvendor problem (Chen et al., 2017; Ma, 2019). Considering inventory and pricing decisions simultaneously was first presented by Whitin in 1995. However, in his research, only inventory level decisions including optimum quantity were considered. Remark that with uncertain demand, one-shot or seasonal decisions, and competitive markets, the newsvendor model is applicable and shining. However, the determination of overage and underage costs, products with missing shelf life, and completely non-predictable demand are the main circumstances that the newsvendor model cannot result in beneficial responses (Huber et al., 2019; Guo et al., 2019; Ma, 2019).

The proposed model and solving methodology of this article are comparable with previous studies. First, a set of relevant papers examined the single product newsvendor case. These papers usually extended the classic newsvendor problem in different directions. Some research works considered extending the newsvendor model with different risk measures (Sévi, 2010; Wu et al., 2013; Arıkan and Fichtinger, 2017; Vipin and Amit, 2017; Agrawal and Singh, 2019). Some others investigated the pricing problems along with ordering in newsvendor problem (Wang et al., 2014; Hu and Su, 2018; Rubio-Herrero and Baykal-Gürsoy, 2018; Mitra, 2018; Kyparisis and Koulamas, 2018; Mohammadivojdan and Geunes, 2018; Ma, 2019). The Data-driven newsvendor problem to approximate demand using available datasets and machine learning-based solution methods were also studied (Huber et al., 2019). Güler et al. (2018) also examined a duopoly problem when two suppliers exist to procure the product. Beyond their extensions, all of the above-mentioned studies only focused on the economic pillar of sustainability. Tsao et al. (2017) formulated a single-product newsvendor model considering trade risk and carbon emission. Similarly, Rogetzer et al. (2019) also formulated the newsvendor problem considering environmental issues.

Furthermore, a variety of studies extended the newsvendor model considering multiple products. These studies usually formulated just the economic pillar with different assumptions. For instance, Reimann (2011) formulated a multi-product newsvendor where newsvendor was capable to either use speculative production or anticipatively reserve capacity to respond to uncertain demands. Zhang (2012) proposed a multi-tier binary solution method based on the Karush-Kuhn-Tucker (KKT) method to develop an algorithm for solving the multi-constraint newsvendor problem with general demand distribution. Moreover, Zhang and Yang (2016) studied a two-product, multi-tier newsvendor when the total demands of two products are fixed. Similarly, Fu et al. (2017) also studied two-product newsvendors considering flexible products. Also, Murarka et al. (2019) modeled a multi-product newsvendor problem considering conditional value at risk. Recently Wang and Choi (2020) presented a novel Newsvendor model and employed the Lagrange Multipliers and KKT conditions to optimize the model subject to emission constraint. By and large, comparing relevant literature with the current study, the first stream of single-product cases is extended by considering multiple products. On the other hand, the main novelty of the current paper regarding the multi-product studies is to consider all the pillars of sustainability beyond the single economic pillar. In Table 1, relevant articles have been illustrated to present the possible research gaps. As shown, previous research works are categorized based on the product (single or multi), demand type, pillars of sustainability considered in the objective functions, validation approach of the proposed model, uncertainty parameter, proposed/developed solving approach/algorithm, and variables considered for optimizing.

As mentioned above, few research works focused on developing and designing new algorithms for solving multi-product newsvendor problems (e.g. Mohammadivojdan and Geunes, 2018; Murarka et al., 2019). In this regard, the novelty of the current research is developing a multi-objective model consist of all the pillars of sustainability. Beyond the classic economic pillar of newsvendor problems being formulated as the total profit function, similar to all the reviewed studies, two other pillars of environmental and social effects are also formulated in this research. Moreover, all aspects and objectives of sustainability have only been evaluated by a few research works and especially for single product newsvendor. Almost in all of the studies, the economic pillar of sustainability was formulated as the profit of a single or all of the products. This objective was formulated as the sum of revenue obtained from selling the products in the usual time and the revenue from salvaging unsold items at the end of the selling season, minus the costs of product processing and shortage. In a few studies, e.g. Tsao et al. (2017), Rogetzer et al. (2019), and Schulte and Sachs (2020), the sustainability pillars were also modeled in a single objective by adding or subtracting the costs due to emission or the profit from recycling or defining a service level of responding customers demand on time. In fact, the environmental effects were transformed into equivalent economic effects. However, in this proposed research multi-product, multi-objective and sustainability issues have been considered simultaneously for the model designation. In the proposed model, while the economic pillar is formulated with similar logic, other sustainability pillars are modeled separately by considering their own characteristic. Moreover, in the model formulation, no restriction has been set for product demands to follow a predetermined distribution. Accordingly, three continuous distribution functions including normal, uniform and exponential distributions are considered in the case study. Remark that, for more clarification, a real-world case study from the Fast-moving consumer goods (FMCG) industry with real data has been employed alongside sensitivity analysis. Applying real-world data for newsvendor problems were rarely investigated (e.g. Guo et al., 2019; Huber et al., 2019). Also, considering the non-commensurability of the formulated objectives, a Lagrange relaxation sub-gradient optimization algorithm is developed to solve the model. The authors believe that a combination of different probabilistic distribution, three sustainability pillars, multi-objective model, and multi-product newsvendor problem have not been previously considered by other scholars. Besides, the authors have developed and designed a new algorithm for this matter instead of employing existing ones.

3. Modeling multi-objective sustainable newsvendor problem

In this study, a two-stage, multi-location, multi-item, multi-objective, capacitated newsvendor problem is formulated considering sustainability considerations. According to Hausschild et al. (2013), Rohmer et al. (2019), and according to sustainability pillars, different criteria are applicable to formulate the problem. This paper aims to study a two-stage procurement system, as illustrated in Fig. 1, including a central warehouse that covers the demands of several regional warehouses on some products. The demand for regional branches could adopt exponential, normal, or uniform distribution functions. In case the inventory level is considered as q, each unit of demand above q is lost in potential sales and a single period inventory control model is applied. Note that the proposed model considers multi-product inventory systems. Moreover, three objective functions for three pillars of sustainability have been considered. In the following subsections, the used notations and equations are described.

3.1. Notation

Sets

I Set of regional warehouses (demand nodes) indexed by i;

N Set of products indexed by n;

K Set of vehicles indexed by k;

F set of sustainability criteria (environmental or social) indexed by f;

Parameters

D_{in} Demand for product n in regional warehouse i that follows the statistical distribution $F_{in}(x) = Pr(D_n \leq x)$ with density function f_{in};

Mean of demand for product n in regional warehouse i;
α_{in} Percent of scraped or unusable items remaining at the end of the period that should be disgraced of product n;
p_n Retail price for each unit of product n;
c_{wn} The marginal cost of the central warehouse to procure (produce) each unit of product n;
c_{in} The marginal cost of regional warehouse i to buy each unit of product n;
b_{wn} Shortage cost of the central warehouse for each unit of product n;
b_{in} Shortage cost of regional warehouse i to buy each unit of product n;
v_{in} Salvage cost earned from each unit of unsold product n at regional warehouse i;
s_{fn} The performance of each unit of product n being produced concerning sustainability factor f;
v_i The storage capacity of regional warehouse i for a single period;
C Procurement capacity of the central warehouse for a single period;
a_n Storage requirement of each unit of product n;
c_n Per capita production capacity required for producing each unit of product n;
Decision Variable
q_{in} Quantity of product n being ordered by regional warehouse i;

3.2. Modeling

As previously mentioned, this study aims to develop a multi-objective and multi-product model considering sustainability to analyze the newsvendor-based framework of the considered procurement system. The problem is a two-stage, multi-location, multi-item, multi-objective, capacitated newsvendor model, which is formulated in three pillars of sustainability, i.e. economic, environmental and social criteria based on the TBL model.

Economic factor modeling. The economic impact of the problem is formulated as an ordinal newsvendor model that seeks to maximize the profit of the system including the sum of central warehouse and regional warehouses profit. The economic perspective of the problem is investigated extensively and, in this section, the associated results are briefly expressed. According to Tsay (2001), Cachon (2003), Hellermann (2006), the expected sale, ES, expected inventory at the end of a period EI and expected lost sale ELS, of a single regional warehouse i for a single item n is formulated as follows, respectively.

$$ES(q_{in}) = q_{in} - \int_0^{q_{in}} F_{in}(y)dy \tag{4}$$

$$EI(q_{in}) = q_{in} - ES(q_{in}) \tag{5}$$

$$ELS(q_{in}) = \mu_{in} - ES(q_{in}) \tag{6}$$

In the above equations, ES is determined as the expected value of sale considering the ordering quantity of q. i.e. $ES(q_{in})$ equals to q_{in} with a probability $Pr(D_n \geq q_{in})$ and is equal to any value of $y \in [0, q_{in}]$ with a probability $f_{in}(y)$. Therefore,

$$ES(q_{in}) = q_{in}.Pr(D_n \geq q_{in}) + \int_0^{q_{in}} yf_{in}(y)dy = q_{in}(1 - F_{in}(q_{in})) + \int_0^{q_{in}} yf_{in}(y)dy$$

Using integration by parts, the above equation is transformed into Eq. (5). The $EI(q_{in})$ means that if an order quantity q_{in} is issued, the expected inventory on hand at the end of sale period for any values of sale $y \leq q_{in}$ is $(q_{in} - y)$ with a probability of $f_{in}(y)$. Therefore,

$$EI(q_{in}) = \int_0^{q_{in}} (q_{in} - y)f_{in}(y)dy = q_{in}F_{in}(y) - \int_0^{q_{in}} yf_{in}(y)dy = q_{in}F_{in}(y)$$
$$+ q_{in}(1 - F_{in}(y)) - ES(q_{in}) = q_{in} - ES(q_{in}) = q_{in}$$

As illustrated in Eq. (5). In a similar manner, $ELS(q_{in})$ for a given order quantity of q_{in} equals to $(y - q_{in})$ for any values of sale $y \geq q_{in}$ with a probability of $f_{in}(y)$. Defining $ELS(q_{in}) = \int_{q_{in}}^{\infty} (y - q_{in})f_{in}(y)dy$ and following a similar argument like $EI(q_{in})$, the Eq. (6) is obtained. Beyond different schemes of modeling newsvendor problems in the relevant literature, the mathematical themes are usually similar (Abdel-Malek and Areeratchakul, 2007; Vipin and Amit, 2019). In this paper, the formulation proposed by Cachon (2003) is developed. Considering cost and profit parameters, the expected profit of regional warehouse i is formulated as follows.

$$P_i = p_n ES(q_{in}) + v_{in} EI(q_{in}) - b_{in} ELS(q_{in}) - c_{in} q_{in}$$
$$= (p_n - v_{in} + b_{in})ES(q_{in}) - (c_{in} - v_{in})q_{in} - b_{in}\mu_{in} \tag{7}$$

That means the profit of regional warehouse i (defined as its revenue obtained from selling the expected amount of $ES(q_{in})$ plus the salvage revenue due to salvaging the unsold amount of products) is expected as $EI(q_{in})$. On the other hand, the costs associated with product shortage and the marginal cost of processing q_{in} is subtracted along with the transferring payment from the warehouse revenue. Besides, the corresponding profit function of the central warehouse is equal to its revenue from transfer payment T_{ic} minus the shortage and procurement cost as follows.

$$P_{Cw} = b_{wn} ES(q_{in}) - c_{wn} q_{in} - b_{wn}\mu_{in} \tag{8}$$

Therefore, the supply chain profit of the two-player network with a single item is transferred as follows.

$$P = P_i + P_{Cw}$$
$$= (p_n - v_{in} + b_{wn} + b_{in})ES(q_{in}) - (c_{wn} + c_{in} - v_{in})q_{in} - (b_{wn} + b_{in})\mu_{in} \tag{9}$$

By constructing and aggregating the functions of Equation (9) for each item at each regional warehouse, the final economic factor model is obtained as follows (Abdel-Malek, Areeratchakul, 2007; Turken et al., 2012).

$$TP = \sum_{i=1}^{I} \sum_{n=1}^{N} \left[(p_n - v_{in} + b_{wn} + b_{in}) \left(q_{in} - \int_0^{q_{in}} F_{in}(y)dy \right) - (c_{wn} + c_{in} - v_{in})q_{in} - (b_{wn} + b_{in})\mu_{in} \right] \tag{10}$$

Environmental and social factor modeling. The manufacturing system leads to significant impacts on the environment. To consider these negative effects, two dimensions are discussed. Suppose that sustainability factor F is decomposed into $\{F', F''\}$ where F' are sustainability factors affected by the production system, and F'' are sustainability factors due to unusable or scraped salvage items. Therefore, the sustainability function of the newsvendor model is formulated as a bi-objective model. The first part of this model is related to the sustainable impacts of producing the products required by regional warehouses. Since in each planning period, a magnitude of q_{in} is ordered from regional warehouse i for product n, total sustainability impact of production for the whole system concerning sustainable factor $f \in F'$ is formulated as follows.

$$SIP_{f'} = \sum_{i=1}^{I} \sum_{n=1}^{N} s_{f'n} \cdot q_{in}, \ \forall f' \in F' \tag{11}$$

On the other hand, a portion α_{in} of any unsold product is being scraped and should be disgraced. This leads to a negative potential impact on the environment and society, e.g. Ferdan et al. (2018) discussed the greenhouse gas emission from non-recyclable municipal waste treatment. Pujara et al. (2019) also estimated that under the current scenario of waste management, a magnitude of 164–735 tonnes of waste is generated per year. As another clue, 15–20% of total municipal solid waste and 50% of total world plastic waste is due to packaging (Meherishi et al., 2019). In some countries, 70% of waste is dumped in landfill sites (Horodytska et al., 2020). Waste management has direct and indirect impacts on social aspects as reviewed by Ibáñez-Forés et al. (2019). Their review identified 12 categories of social impacts of waste management like working rights, human rights, health and safety, community satisfaction and participation, etc. Therefore, the sustainability impacts of unsold items are formulated as follows.

$$SIU_{f''}=\sum_{i=1}^{I}\sum_{n=1}^{N}s_{f''n}(\alpha_{in}.EI(q_{in})),\ \forall f''\in F'' \tag{12}$$

In the above equation, $\alpha_{in}EI(q_{in})$ is the amount of scrapped expected unsold items at the end of the planning period and creates an amount of $s_{f''n}(\alpha_{in}EI(q_{in}))$ of scrapped items. Considering the three sustainability objectives, i.e. Eq. (10)–(12), it is clear that while Eq. (10) seeks to optimize the economic performance of the ordering policy, the next two objectives try to optimize the environmental impact of the ordering policy by considering its direct, i.e. Eq. (11), and indirect impacts of unsold items, i.e. Eq. (12), simultaneously.

Model constraints. Two constraints are imposed over the considered system. The first constraint is related to the procurement capacity of the central warehouse. Each unit of product (*n)* occupies a production capacity portion c_n which should not totally exceed the available production capacity know as (C). Therefore, it requires the following limitation.

$$\sum_{n=1}^{N}\sum_{i=1}^{I}c_n q_{in}\le C \tag{13}$$

Furthermore, each regional warehouse *i* has a limited storage capacity known as v_i. Therefore, the number of products being ordered by a specific regional warehouse must be lower than its storage capacity as follows.

$$\sum_{n=1}^{N}a_n q_{in}\le v_i,\forall i\in\{1,2,\dots,I\} \tag{14}$$

Aggregating equations (4)–(14), the multi-objective and multi-product sustainable newsvendor model is formulated as Eq. (15).

$$Max\ Z_1=\sum_{i=1}^{I}\sum_{n=1}^{N}\left[(p_n-v_{in}+b_{wn}+b_{in})\left(q_{in}-\int_0^{q_{in}}F_{in}(y)dy\right)-(c_{wn}+c_{in}-v_{in})q_{in}-(b_{wn}+b_{in})\mu_{in}\right]$$

$$Max\ Z_{2f'}=\sum_{i=1}^{I}\sum_{n=1}^{N}s_{f'n}\cdot q_{in},\ \forall f'\in F'$$

$$Max\ Z_{3f''}=\sum_{i=1}^{I}\sum_{n=1}^{N}s_{f''n}\alpha_{in}\left(\int_0^{q_{in}}F_{in}(y)dy\right),\ \forall f''\in F''$$

$$\sum_{n=1}^{N}\sum_{i=1}^{I}c_n q_{in}\le C$$

$$\sum_{n=1}^{N}a_n q_{in}\le v_i,\forall i\in\{1,2,\dots,I\}q_{in}\ge 0 \tag{15}$$

4. Compromise programming approach

Formulating the multi-objective problem as discussed in the previous section, a method is required to determine its solution. Some methods like the Lexicographic method define a hierarchy of objectives and then find the optimal solution of an objective after optimizing all of its above objectives. While this hierarchical method of solving multi-objective problems identifies a set of efficient solutions for the problem, it might be possible that the obtained solutions are not satisfactory based on all objectives, i.e. some objectives in the lower ranks never attained their optimum or even getting close to it. Therefore, a multi-objective approach where all the objectives are considered simultaneously requires to first determine an efficient solution and next seek a satisfactory solution according to different objectives. By compromise programming, a multiple-criteria decision-making technique, any decision-maker seeks a solution as close as possible to the ideal point (Ringuest, 1992). To achieve this closeness, compromise programming uses the family of L_p metrics given by expression (16) as follows.

$$L_p(w)=\left[\sum_j w_j^p\left|\frac{Z_j^*-Z_j}{Z_j^*}\right|^p\right]^{\frac{1}{p}} \tag{16}$$

Where w_j measures the relative importance of the *j*th objective, Z_j^* is the ideal value of the *j*th objective and is determined by the single-objective optimization of Z_j. The introduction of the relative weight vector *w* aids the decision-maker to compensate for their preferences over different objectives. The parameter *p* takes any values from 1, 2, …,∞. Here, the authors assume p = 1; thus, considering the multi-objective problem in (15) with 1+|F'|+|F''| objectives, the best-compromise solution minimizes the following equation.

$$Z=w_1'\times(Z_1^*-Z_1)+\sum_f w_{2,f}'\times\left(Z_{2,f}^*-Z_{2,f}\right)+\sum_{f'}w_{3,f'}'\times\left(Z_{3,f'}^*-Z_{3,f'}\right) \tag{17}$$

Where. $w_j'=w_j/Z_j^*$

Substituting Z_j into the equation (17) and considering the system constraints, the authors present the following single objective problem.

$$Min\ Z=-w_1'\times\sum_{i=1}^{I}\sum_{n=1}^{N}\left[(p_n-v_{in}+b_{wn}+b_{in})\left(q_{in}-\int_0^{q_{in}}F_{in}(y)dy\right)-(c_{wn}+c_{in}-v_{in})q_{in}-(b_{wn}+b_{in})\mu_{in}\right]$$
$$-\sum_f\sum_{i=1}^{I}\sum_{n=1}^{N}w_{2,f}'\cdot s_{fn}\cdot q_{in}-\sum_{f'}\sum_{i=1}^{I}\sum_{n=1}^{N}w_{3,f'}'s_{f''n}\alpha_{in}\left(\int_0^{q_{in}}F_{in}(y)dy\right)$$
$$+\left\{w_1'\times Z_1^*+\sum_f w_{2,f}'\times Z_{2,f}^*+\sum_{f'}w_{3,f'}'\times Z_{3,f'}^*\right\}\sum_{n=1}^{N}\sum_{i=1}^{I}c_n q_{in}\le C$$

$$\sum_{n=1}^{N}a_n q_{in}\le v_i,\forall i\in\{1,2,\dots,I\}$$

$$q_{in}\ge 0 \tag{18}$$

Since the developed model in (18) is nonlinear, a Lagrange relaxation approach is proposed using a sub-gradient optimization algorithm. To validate the results obtained by the proposed method, GA and SA are also designed for comparison purposes.

Start
Initialize $\pi \in (0,2)$
Initialize $\lambda^0 = [\lambda_1^0, \lambda_2^0, \cdots, \lambda_I^0, \lambda_c^0]$

Repeat
Given λ^k values, use Eq. (17) to get q_{in}^k, then Eq. (16) to get the lower bound Z_{lb}^k.
Calculate the sub-gradient of the multiplier λ_i^k as $G_i^k = \sum_{n=1}^N a_n q_{in}^k - v_i$ for $i = 1,2,\ldots,I$.
Calculate the sub-gradient of the multiplier λ_c^k as $G_c^k = \sum_{n=1}^N \sum_{i=1}^I c_n q_{in}^k - C$.
Calculate the step size $\theta^k = \pi(Z_{ub} - Z_{lb}^k)/\left[\left(G_c^k\right)^2 + \sum_i \left(G_i^k\right)^2\right]$.
Update $\lambda_i^{k+1} = \max(0, \lambda_i^k + \theta^k \times G_i^k)$ for $i = 1,2,\ldots,I$.
Update $\lambda_c^{k+1} = \max(0, \lambda_c^k + \theta^k \times G_c^k)$.

Until stopping condition

4.1. The proposed Lagrangian relaxation approach with sub-gradient optimization

4.1.1. Lagrangian relaxation

The authors propose a solution approach based on the well-known Lagrangian Relaxation technique. The Lagrangian relaxation of the model in Equation (18) is defined as follows.

$$\begin{aligned}\mathscr{L}(q,\lambda,\lambda_i) = & -w_1^{'}\sum_{i=1}^{I}\sum_{n=1}^{N}\left[(p_n - v_{in} + b_{wn} + b_{in})\left(q_{in} - \int_0^{q_{in}} F_{in}(y)dy\right)\right.\\ & \left. - (c_{wn} + c_{in} - v_{in})q_{in} - (b_{wn} + b_{in})\mu_{in}\right] - \sum_{f}\sum_{i=1}^{I}\sum_{n=1}^{N} w_{2,f}^{'} s_{fn} q_{in}\\ & - \sum_{f'}\sum_{i=1}^{I}\sum_{n=1}^{N} w_{3,f'}^{'} s_{f''n}\alpha_{in}\left(\int_0^{q_{in}} F_{in}(y)dy\right)\\ & + \left\{w_1^{'} \times Z_1^* + \sum_f w_{2,f}^{'} \times Z_{2,f}^* + \sum_{f'} w_{3,f'}^{'} \times Z_{3,f'}^*\right\}\\ & + \lambda_c\left[\sum_{n=1}^{N}\sum_{i=1}^{I} c_n q_{in} - C\right] + \sum_{i=1}^{I}\lambda_i\left[\sum_{n=1}^{N} a_n q_{in} - v_i\right]\end{aligned} \tag{19}$$

The KKT conditions (Ye, 2006) for multiple inequality constraints result as follows.

$$\lambda_c\left[\sum_{n=1}^{N}\sum_{i=1}^{I} c_n q_{in} - C\right] = 0 \tag{21}$$

$$\lambda_i\left[\sum_{n=1}^{N} a_n q_{in} - v_i\right] = 0 \ \forall i \tag{22}$$

$$\sum_{n=1}^{N}\sum_{i=1}^{I} c_n q_{in} \le C \tag{23}$$

$$\sum_{n=1}^{N} a_n q_{in} \le v_i, \forall i \tag{24}$$

$$\lambda_c, \lambda_i \ge 0, \ \forall i \tag{25}$$

Proof. See below for proof of equation (20) by taking the partial derivative on q_{in}. Note that the Hessian matrix is proved to be definitely positive.

$$\frac{\partial \mathscr{L}(q,\lambda_c,\lambda_i)}{\partial q_{in}} = 0, \ \forall i, n \rightarrow$$

$$\begin{aligned}& -w_1^{'}[(p_n - v_{in} + b_{wn} + b_{in})(1 - F_{in}(q_{in})) - (c_{wn} + c_{in} - v_{in})]\\ & \quad - \sum_f w_{2,f}^{'} s_{fn} - \sum_{f'} w_{3,f'}^{'} s_{f''n}\alpha_{in} F_{in}(q_{in}) + \lambda_c c_n + \lambda_i a_n = 0, \ \forall i, n\end{aligned} \tag{26}$$

$$p(D_{in} \le q_{in}) = \frac{w_1^{'}(p_n - v_{in} + b_{wn} + b_{in}) - w_1^{'}(c_{wn} + c_{in} - v_{in}) + \sum_f w_{2,f}^{'} s_{fn} - \lambda_c c_n - \lambda_i a_n}{w_1^{'}(p_n - v_{in} + b_{wn} + b_{in}) - \sum_{f'} w_{3,f'}^{'} s_{f''n}\alpha_{in}}, \ \forall i, n \tag{20}$$

Accordingly, the following equation emanates.

$$F_{in}(q_{in}) = p(D_{in} \le q_{in}) = \frac{w'_1(p_n - v_{in} + b_{wn} + b_{in}) - w'_1(c_{wn} + c_{in} - v_{in}) + \sum_f w'_{2,f} s_{fn} - \lambda_c c_n - \lambda_i a_n}{w'_1(p_n - v_{in} + b_{wn} + b_{in}) - \sum_{f'} w'_{3,f'} s_{f''n} \alpha_{in}}, \ \forall i, n \tag{27}$$

Furthermore, for constructing the Hessian matrix, using (26) and taking the second-order partial condition, the results are achieved as follows.

$$\frac{\partial^2 \mathscr{L}(q, \lambda_c, \lambda_i)}{\partial q_{in}^2} = f_{in}(q_{in}) \left[w'_1(p_n - v_{in} + b_{wn} + b_{in}) - \sum_{f'} w'_{3,f'} s_{f''n} \alpha_{in} \right], \ \forall i, n \tag{28}$$

$$\frac{\partial^2 \mathscr{L}(q, \lambda_c, \lambda_i)}{\partial q_{i,n} q_{i1,n1}} = 0, \ \forall i, i1, n, n1 \tag{29}$$

The Hessian matrix is a diagonal matrix in which the entries are equal to (28); thus, always takes a positive value.

4.1.2. Determining the ideal points

As said before, the ideal point of jth objective is determined by a single objective problem with maximizing Z_j subject to system constraints and neglecting other objectives. Determining Z_1^* is equivalent to solve the system of equations 20–25 with $w'_1 = 1$ and keeping the remaining importance weights equal to zero. Since the optimizing Z_{2g} for each $g \in F'$ regarding the capacity constraints is a linear model, any available optimization software is applicable to solve it. The authors employed GAMS 23.5 to obtain the ideal value of Z_{2g}^*. Moreover, determining Z_{3g}^*, for each $g \in F''$ is equivalent to solve the system of equations 20–25 with $w'_{3,g} = 1$, and keeping the remaining importance weights equal to zero.

4.1.3. Sub-gradient optimization

Sub-gradient Optimization is an iterative algorithm for minimizing convex functions. Given a vector λ^k at iteration k, the authors proposed to calculate the new iterate λ^{k+1}. The sub-gradient method simply states that the new iterate should be along the direction of the sub-gradient with a properly selected step length of θ^k. The algorithm is given in the following. The step size is calculated using a well-known formula that works in practice. Note that positive values for G_c^k and G_i^k show the exceeded capacity constraints for the central warehouse and ith warehouse, respectively. Assuming $G'^k_c = \max(0, G_c^k)$ and $G'^k_i = \max(0, G_i^k)$ as the exceeded amount of capacities, at each iteration k, the stopping condition is defined as $\lambda_c^k G'^k_c + \sum_{i=1}^{I} \lambda_i^k G'^k_i < \varepsilon$ where $\varepsilon = 0.01$. The proposed solution approach based on the classical sub-gradient optimization algorithm is as follows.

4.2. Genetic algorithm

In this section, GA is designed to solve the problem. After generating the initial population, the evolutionary process of GA incorporating operations of selection, crossover, mutation, and repair is continued until the termination condition is satisfied.

4.2.1. Solution representation scheme and initial solution

A chromosome is represented by a two-dimensional matrix $Q = [q_{in}]_{I \times N}$ including I rows and N columns. The element q_{in} represents the

SA Algorithm
Input *parameters:* T_0, T_f, N, *and* α
$T = T_0$
S = Generate an initial solution and repair it as explained in section 4.2.1 and 4.2.4
Z_s *= Cost of S*
Update best solution as Best = S and $Z^* = Z_s$
While *(T > Tf)* **Do**
  for *i = 1 to N* **Do**
    nbr = Generate neighbor solution of S and repair it as explained in section 4.2.4
    Z_{nbr} *= Cost of nbr*
    $\Delta = Z_{nbr} - Z_s$
    if $Z_{nbr} <= Z_s$ **then**
      S=nbr
      $Z_s = Z_{nbr}$
      Update best solution as Best = S and $Z^* = Z_s$
    Elseif $e^{-\Delta/T} <$ *random(0,1)* **then**
      S=nbr
      $Z_s = Z_{nbr}$
    Endif
  Endfor
  Decrease temperature as $T = \alpha \times T$
Endwhile

order quantity of product n to be ordered by the regional warehouse i. The procedure for generating the initial population including N_{pop} solutions is as follows. To generate a random solution, for each i and n, a quantity between 0 and $\overline{q}_{in}$ is randomly assigned. The amount of $\overline{q}_{in}$ is determined based on the demand distribution function (D_{in}) and the capacity constraint (14). Based on the capacity constraint (14), the maximum amount of q_{in} is v_i/a_n. Moreover, q_{in} cannot exceed b for the Uniform demand distribution function, i.e. $D_{in} = U(a,b)$. Thus, $\overline{q}_{in} = v_i/a_n$ for either the Normal and Exponential demand distribution function, and $\overline{q}_{in} = \min(v_i/a_n, b)$ for the Uniform demand distribution function $D_{in} = U(a,b)$.

4.2.2. Fitness evaluation and selection

The fitness of each solution in the population is computed using the objective function in Eq (17). For the selection process, a roulette-wheel selection method is applied in which, the probability of choosing an individual for the next generation is proportional to its fitness, the better the fitness is, the higher chance for that individual to be chosen.

Table 2
Value of GA parameters at each level.

Parameter	Level 1	Level 2	Level 3
Npop	15	30	45
Pc	0.6	0.7	0.8
Pm	0.15	0.2	0.25

4.2.3. Crossover and mutation

For the crossover process, the uniform crossover method is applied. Assume that a pair of parents are selected for crossover according to the crossover rate P_c. Let $[q^1_{in}]_{I\times N}$ and $[q^2_{in}]_{I\times N}$ to be the chromosomes of parents, respectively. First, a matrix $T = [\tau_{in}]_{I\times N}$ including I rows and N columns is randomly generated between 0 and 1. Then, new offspring is determined as $q'_{in} = q^1_{in} \times \tau_{in} + q^2_{in} \times (1-\tau_{in})$ and $q''_{in} = q^1_{in} \times (1-\tau_{in}) + q^2_{in} \times \tau_{in}$ for i = 1,..,I and n = 1, …,N. Newly generated solutions are typically mutated before being added to the population. In the mutation process, each q_{in} is selected according to the mutation rate Pm. If selected, first a random number is generated as $r \in [-0.20, 0.2]$. Then, the new value is calculated as $q_{in} = q_{in} \times (1 + r)$. In other words, q_{in} up to 20% decreases/increases.

4.2.4. Repair

To avoid infeasible solutions, a repair algorithm is applied as shown in the following. For each warehouse i, the expression $\sum_n a_n q_{in} - v_i$ is calculated and stored in variable 'A'. In case of the capacity violation of the warehouse i (i.e. $A > 0$), a product is selected randomly and the corresponding order quantity (q_{in}) is reduced such that the required capacity of the warehouse i is equal to v_i. This may cause q_{in} to be zero which means that there is still a capacity violation and this procedure must continue until variable A becomes zero. Capacity violations for the central warehouse may also exist. In this case, by defining variable 'B", a regional warehouse and a product is selected randomly and a similar procedure must continue until variable B becomes zero. The repair

Table 3
Value of SA parameters at each level.

Parameter	Level 1	Level 2	Level 3
T_0	200	500	1000
A	0.95	0.97	0.99
N	5	10	15

Table 4
The results of experiments for GA.

Experiment	Npop	Pc	Pm	Observations (5 runs)				
1	1	1	1	0.3201	0.3468	0.3134	0.3128	0.3069
2	1	2	2	0.2942	0.2856	0.2740	0.2750	0.2918
3	1	3	3	0.2899	0.3088	0.3241	0.2872	0.3245
4	2	1	2	0.3037	0.3349	0.3630	0.3178	0.3060
5	2	2	3	0.3068	0.3183	0.2944	0.3141	0.3017
6	2	3	1	0.3397	0.3186	0.3160	0.3131	0.3157
7	3	1	3	0.3170	0.3141	0.3216	0.3129	0.3285
8	3	2	1	0.3614	0.3360	0.3317	0.3302	0.3407
9	3	3	2	0.3197	0.3215	0.3319	0.3402	0.3444

Table 5
The results of experiments for SA.

Experiment	T_0	α	N	Observations (5 runs)				
1	1	1	1	0.3222	0.3043	0.3357	0.3444	0.3196
2	1	2	2	0.272	0.3057	0.2876	0.2775	0.3276
3	1	3	3	0.3167	0.3628	0.3063	0.3746	0.3193
4	2	1	2	0.31669	0.3102	0.3124	0.3326	0.2939
5	2	2	3	0.3234	0.3007	0.3486	0.3421	0.2865
6	2	3	1	0.3475	0.3147	0.3526	0.3136	0.3135
7	3	1	3	0.3306	0.3252	0.3043	0.3504	0.3327
8	3	2	1	0.3442	0.3158	0.3498	0.3192	0.3331
9	3	3	2	0.275	0.3128	0.3084	0.3324	0.3383

Figs. 2 and 3 demonstrate the Signal noise ratio (S/N) plot, respectively, for GA and SA parameters. Since the biggest S/N value corresponds to the best combination of the parameter values, according to Fig. 2, N_{pop}, P_c, and P_m were selected at the first, second, and third-level, respectively, i.e. $N_{pop} = 15$, $P_c = 0.7$, and $P_m = 0.25$. Similarly, from Fig. 3, it is obvious that $T_0 = 200$, $\alpha = 0.97$, and $N = 10$.

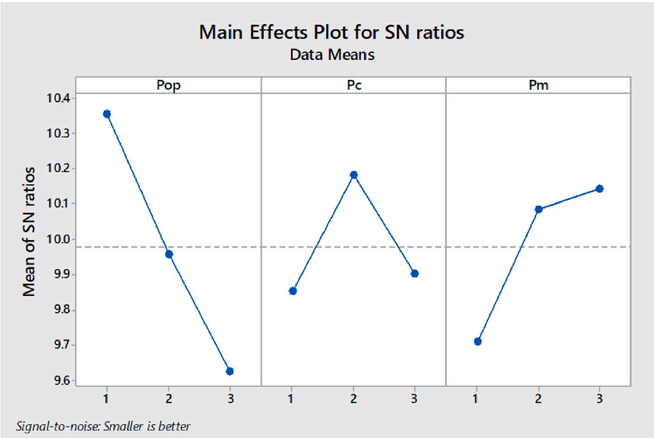


Fig. 2. The S/N ratio for each level of GA parameters.

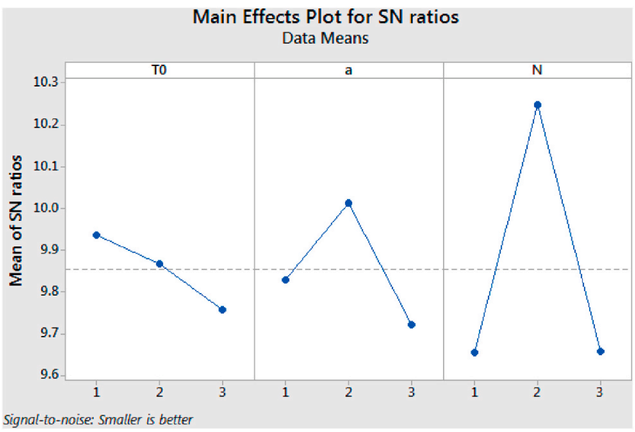


Fig. 3. The S/N ratio for each level of SA parameters.

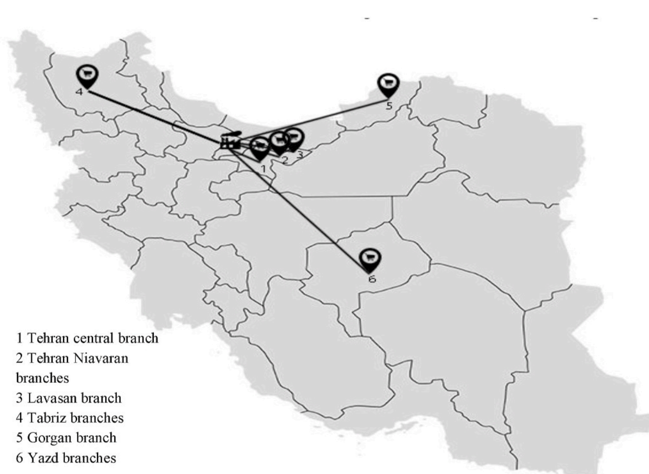


Fig. 4. Warehouses location on the map (source: authors).

algorithm has been presented as follows.

4.2.5. Termination condition

The algorithm stops when an upper limit on the number of generations has been achieved.

Table 6
Products and their corresponding information.

Product name	Retail price ($)	Storage requirement(m^3)
Dark chocolate	9	0.030
Nut chocolate	13.25	0.060
Bitter chocolate	10	0.042
White chocolate	8.16	0.053
Milky chocolate	7.33	0.024

Table 7
Warehouse capacities (m^3).

Warehouse	Central	1	2	3	4	5	6
Capacity	1000	141	176	123	115	104	220

Moreover, the information related to warehouses and products is illustrated in Table 8.

Table 8
Warehouse related information.

Warehouse	Product	Marginal cost	Shortage cost	Salvage cost	Scrap (%)
Central	1	1.5	1.1	-	-
	2	2.7	0.7	-	-
	3	3.1	1.3	-	-
	4	2.1	1.9	-	-
	5	4.0	1.4	-	-
1	1	3.4	1.7	0.5	15
	2	1.7	2.0	0.4	10
	3	3.8	0.6	0.1	5
	4	4.1	1.6	0.2	10
	5	1.7	0.6	0.4	8
2	1	0.7	0.1	0.1	5
	2	2.7	1.4	0.2	10
	3	2.2	0.6	0.1	5
	4	1.3	0.8	0.2	5
	5	1.9	0.2	0.1	5
3	1	2.4	0.5	0.1	5
	2	4.3	0.8	0.2	10
	3	3.9	1.5	0.6	15
	4	2.1	0.3	0.1	5
	5	4.9	1.2	0.2	10
4	1	2.6	0.6	0.4	8
	2	1.6	0.4	0.2	5
	3	3.5	1.4	0.2	10
	4	2.4	0.2	0.1	5
	5	4.0	0.5	0.2	8
5	1	1.4	0.3	0.2	5
	2	3.3	1.6	0.5	15
	3	2.0	0.6	0.2	5
	4	3.7	0.5	0.1	5
	5	1.6	0.4	0.2	5
6	1	2.3	0.2	0.1	5
	2	2.5	0.4	0.1	5
	3	1.6	0.7	0.1	5
	4	2.3	0.8	0.1	5
	5	2.1	0.6	0.4	8

Analyzing historical demand information in different branches and using distribution fitting over this information, the statistical distribution of different product demand in each branch is approximated. These distributions are shown in Table 9.

4.3. Simulated Annealing algorithm

In this section, SA is designed to solve the problem. The algorithm starts from an initial solution and performs a neighborhood search to find better solutions. SA updates the current solution if a candidate solution outperforms the current solution. The algorithm also accepts worse solutions based on a probability value using the metropolis criterion. The probability value is calculated by using the values of the current temperature and the difference between the current and the candidate solution. A cooling schedule is applied in the algorithm to decrease the temperature to decrease the probability of accepting a worse solution over iterations. The authors employed the geometric cooling schedule to decrease the temperature T. The geometric cooling function was given as $T = \alpha \times T, 0 < \alpha < 1$, where α is the temperature reduction rate. The main parameters of the algorithm include initial temperature (T_0), final temperature (T_f), cooling rate (α), and allowed iteration numbers at each temperature (N). The SA algorithm has been presented as follows.

Repair Algorithm

For *each regional warehouse* $i = 1$ *to* I **Do**

  $A = \sum_n a_n q_{in} - v_i$

  While $(A > 0)$ **Do**

    $n \leftarrow$ *an integer random number* $\in [1, N]$

    $q_{old} = q_{in};$

    $\Delta = \min(q_{old}, A / a_n);$

    $q_{in} = q_{old} - \Delta;$

    $A = A - a_n \times \Delta;$

  EndWhile

EndFor

$B = \sum_i \sum_n c_n q_{in} - C;$

While $(B > 0)$ **Do**

  $i \leftarrow$ *an integer random number* $\in [1, I]$

  $n \leftarrow$ *an integer random number* $\in [1, N]$

  $q_{old} = q_{in};$

  $\Delta = \min(q_{old}, B / c_n);$

  $q_{in} = q_{old} - \Delta;$

  $B = B - c_n \times \Delta;$

EndWhile

Table 9
Demand distribution of different products in branches.

Warehouse	Products				
	1	2	3	4	5
1	N(493,89)	E(0.0027)	N(634,45)	U(412,842)	N(850,67)
2	N(632,84)	N(1103,124)	U(528,714)	U(653,1217)	N(1394,98)
3	U(318,793)	E(0.0042)	N(763,103)	U(705,1153)	N(420,75)
4	U(672,982)	E(0.0026)	U(258,763)	N(925,49)	E(0.0018)
5	U(701,1230)	E(0.0030)	E(0.0029)	N(538,73)	N(863,98)
6	N(1302,68)	N(843,43)	E(0.0048)	U(187,439)	E(0.0035)

N: Normal (mean, standard deviation).
U: Uniform(a,b).
E: Exponential(lambda).

Table 10
Sustainability criteria used to formulate the case problem.

Pillar	Criterion	Product type				
		Dark chocolate	Nut chocolate	Bitter chocolate	White chocolate	Milky chocolate
Social	Customers Health	2.5%	3%	3%	2%	2%
Environmental	Reusability of materials	13.9%	19%	13.9%	17%	22%

Table 11
Comparative results of two proposed methods.

Method	Compromise Solution	i	λ_i	G_i	Orders				
					q_{i1}	q_{i2}	q_{i3}	q_{i4}	q_{i5}
The proposed	$Z = 0.24346$	1	0.05416	0	700	693	620	589	882
Lagrangian relaxation	$Z_1 = 57406.03$	2	0.11074	0	658	1043	572	733	1283
approach with sub-gradient	$Z_2 = 498.48$	3	0.04997	0	653	204	814	922	340
optimization	$Z_3 = 41.33$	4	0.06686	0	897	320	494	899	20
		5	0.07990	0	1067	358	190	428	827
		6	0	−62.28	1401	900	436	407	908
		C	0	−183.28					
					q_{i1}	q_{i1}	q_{i1}	q_{i1}	q_{i1}
The proposed	$Z = 0.2497$	1	-	-	701	655	612	568	881
Genetic	$Z_1 = 57289.3$	2	-	-	660	1055	572	744	1227
Algorithm	$Z_2 = 486.2$	3	-	-	693	304	805	947	0
	$Z_3 = 41.25$	4	-	-	933	466	246	910	19
		5	-	-	1200	663	208	0	814
		6	-	-	1411	930	409	392	424
					q_{i1}	q_{i1}	q_{i1}	q_{i1}	q_{i1}
The proposed	$Z = 0.2508$	1	-	-	702	661	614	572	879
Simulated	$Z_1 = 57163$	2	-	-	659	1058	571	738	1253
Annealing	$Z_2 = 489.2$	3	-	-	674	311	802	918	124
Algorithm	$Z_3 = 40.61$	4	-	-	918	389	352	923	19
		5	-	-	1182	452	197	258	819
		6	-	-	1409	936	441	358	534

The convergence behavior and the error gap of the proposed GA and SA are illustrated in Fig. 5(a)–5(d).

Table 12
Detailed Results for different scenarios.

Scenarios	Importance Weights	Compromise Solution	i	λ_i	G_i	Orders q_{i1}	q_{i2}	q_{i3}	q_{i4}	q_{i5}
S_1	$W_1 = 0.70$	$Z_1 = 61877.69$	1	0.01343	0	564	712	631	648	857
	$W_2 = 0.15$	$Z_2 = 472.40$	2	0.12816	0	643	1034	570	761	1267
	$W_3 = 0.15$	$Z_3 = 25.54$	3	0.02527	0	639	199	778	965	335
			4	0.05654	0	865	341	472	911	21
			5	0.06170	0	1061	289	221	487	824
			6	0	−91.89	1348	871	262	364	213
			C	0	−212.89					
S_2	$W_1 = 0.50$	$Z_1 = 59741.70$	1	0.04683	0	641	704	626	607	876
	$W_2 = 0.30$	$Z_2 = 490.02$	2	0.11280	0	657	1039	575	734	1288
	$W_3 = 0.20$	$Z_3 = 33.38$	3	0.04792	0	658	200	803	929	347
			4	0.06741	0	890	321	492	900	28
			5	0.07669	0	1076	320	210	449	832
			6	0	−71.96	1398	898	438	403	522
			C	0	−192.96					
S_3	$W_1 = 0.50$	$Z_1 = 54657.71$	1	0.06001	0	700	708	613	572	895
	$W_2 = 0.20$	$Z_2 = 506.98$	2	0.10869	0	659	1048	570	732	1276
	$W_3 = 0.30$	$Z_3 = 50.08$	3	0.05207	0	647	209	829	913	326
			4	0.06624	0	904	320	496	899	8
			5	0.08317	0	1057	423	169	378	822
			6	0	−52.02	1405	903	435	412	1316
			C	0	−173.02					
S_4	$W_1 = 0.56$	$Z_1 = 61377.22$	1	0.02665	0	575	709	635	638	864
	$W_2 = 0.33$	$Z_2 = 479.76$	2	0.12057	0	651	1032	576	745	1287
	$W_3 = 0.11$	$Z_3 = 27.29$	3	0.03829	0	656	195	784	950	348
			4	0.06488	0	874	329	483	905	33
			5	0.06861	0	1078	274	237	478	832
			6	0	−83.86	1372	884	356	383	280
			C	0	−204.86					
S_5	$W_1 = 0.56$	$Z_1 = 55320.24$	1	0.05642	0	700	704	611	583	883
	$W_2 = 0.11$	$Z_2 = 501.15$	2	0.11125	0	653	1049	567	744	1260
	$W_3 = 0.33$	$Z_3 = 48.51$	3	0.04637	0	638	215	820	928	307
			4	0.06235	0	896	329	488	903	0
			5	0.08259	0	1044	413	159	409	814
			6	0	−58.35	1377	889	342	398	1316
			C	0	−179.35					

To identify the impact of changes in the parameters of the problem on the obtained results, a sensitivity analysis was performed by changing the problem parameters by 10% and 25% and taking one parameter at a time, keeping the remaining parameters at their original values. The effect of parameter changes on Z_1, Z_2, and Z_3 based on different products is illustrated in Fig. 6(a) to 6(c), respectively. It is obvious from Figures (6(a)-6(c)) that among objective functions, Z_3 was highly sensitive to the changes in the values of retail prices, and among products, n_1 impacts more on the objective functions.

4.4. Tuning parameters

Since the quality of solutions obtained by the proposed meta-heuristic algorithms is affected by its parameters, the Taguchi method is used to tune them. There are three parameters to be calibrated for GA; the population size (N_{pop}), the crossover rate (P_c), and the mutation rate (P_m). Moreover, initial temperature (T_0), final temperature (T_f), cooling rate (α), and allowed iteration numbers at each temperature (N) should be calibrated for SA. Given that the parameters T_0, T_f, and α were dependent. Two of them, namely T_0 and α as well as N were taken into account for tuning. The final temperature is assumed to be $T_f = 0.01$. Tables 2 and 3 present these parameters, each with three levels. The Taguchi has been generated using MINITAB 17.1.0.0 software based on the Taguchi L_9 orthogonal arrays design. Both algorithms were executed five times for each experiment and the results are presented in Tables 4 and 5.

5. Case study and results

5.1. Decision context

To illustrate the ability of the proposed methods to solve the considered model, a real-world problem is examined in this section. Fast-moving consumer goods (FMCG) are products that are sold quickly and at a relatively low cost. The industry is important in food and confectionary fields in Tehran as the crowded Capital and megacity city of Iran as an emerging economy. A well-known, large company located in Tehran, EXIR (real name is not mentioned due to confidentiality) produces various products. Its main products include five types of box chocolates (1) white chocolate, (2) milky chocolate, (3) nut chocolate, (4) bitter chocolate, and (5) dark chocolate. Its central warehouse is located in Tehran suburb and covers 5 regional warehouses around the country as (1) Tehran central branch, (2) Tehran Niavaran branch, (3) Lavasan branch, (4) Tabriz branch, (5) Gorgan branch, and (6) Yazd branch. The role of the central warehouse is to procure the demands of these six regional branches according to their orders. These warehouse locations are illustrated in Fig. 4 based on a real map.

This company intends to manage the cost of its transactions with its regional warehouses. At the time, five types of products are distributed in the above network. Table 6 illustrates the monetary information on these products. The price of each product box is mentioned in the second column; however, they are severally packaged in thick coverage to avoid the product's damage while movements. The capacity of warehouses is illustrated in Table 7.

As discussed earlier, beyond normal economic performance, each supply chain deals with sustainability-based impacts that endeavor to control and optimize them. In the considered case study, the sustainability impacts of products are considered along three main pillars of economic, environmental, and social factors. Reviewing the literature and interviewing the FMCG industry experts, the related factors of sustainability in EXIR products are identified as follows.

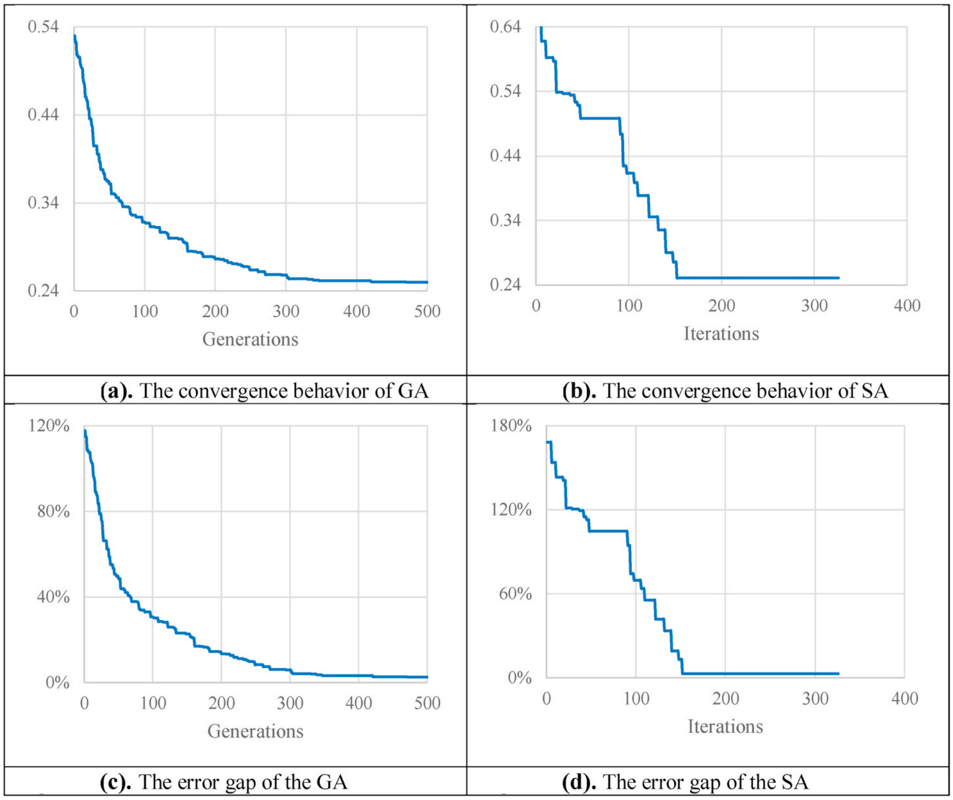


Fig. 5. (a)The convergence behavior of GA. Fig. 5(b). The convergence behavior of SA Fig. 5(c). The error gap of the GA Fig. 5(d). The error gap of the SA.

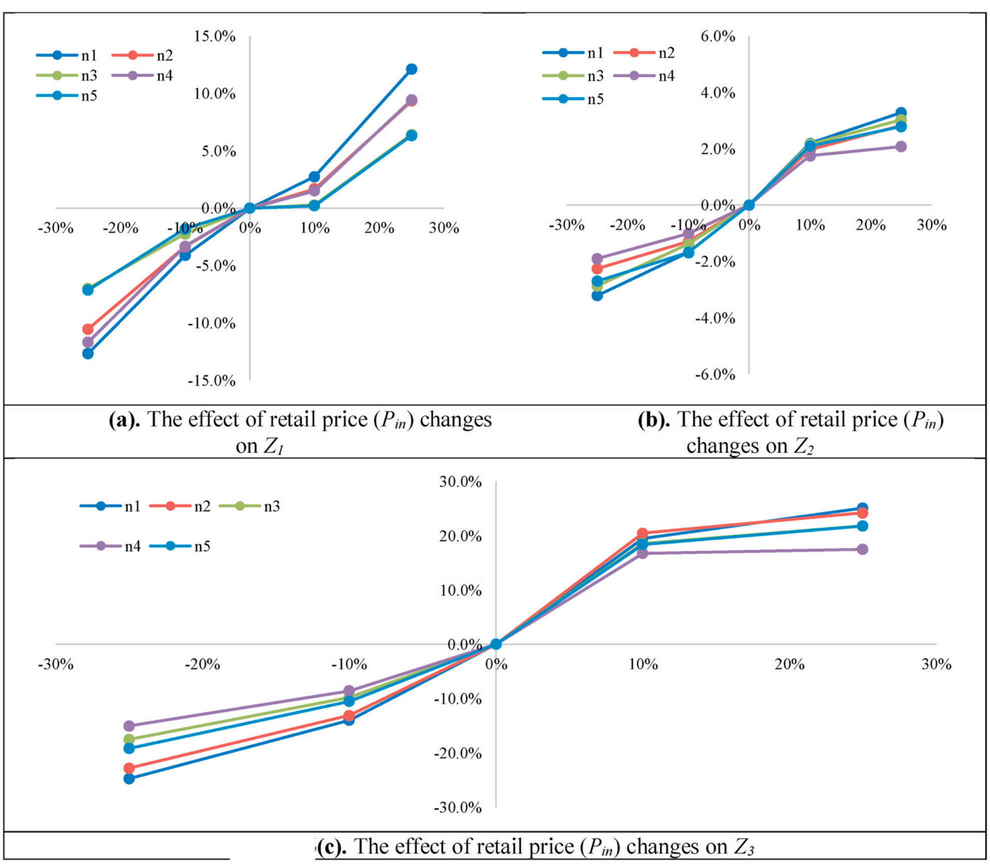
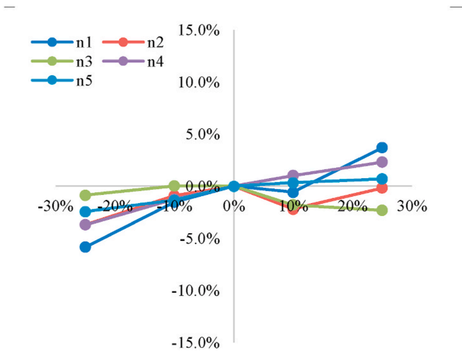
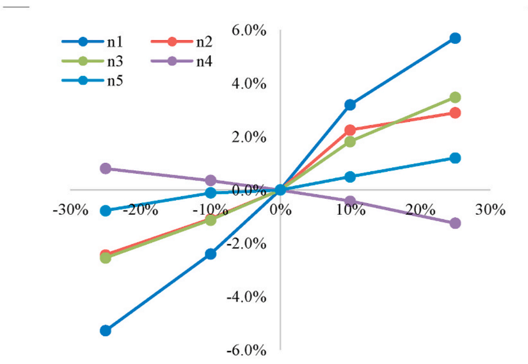


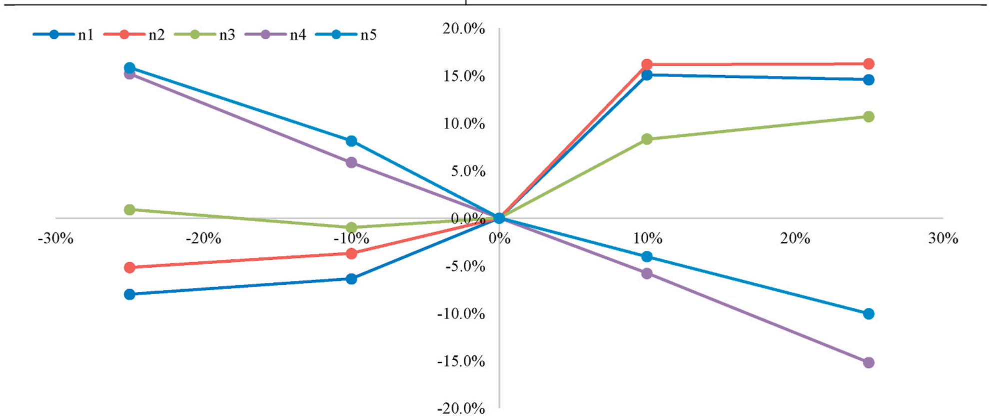
Fig. 6. (a) The effect of retail price (P_{in}) changes on Z_1
Fig. 6(b). The effect of retail price (P_{in}) changes on Z_2 Fig. 6(c). The effect of retail price (P_{in}) changes on Z_3.



(a). The effect of changing the demand means of each product on Z_1



(b). The effect of changing the demand means of each product on Z_2



(c). The effect of changing the demand means of each product on Z_3

Fig. 7. **(a)**The effect of changing the demand means of each product on Z_1
Fig. 7(b). The effect of changing the demand means of each product on Z_2 Fig. 7(c). The effect of changing the demand means of each product on Z_3.

- *Economic pillar: formulated by Z1 as an economic factor.*
  - o The related information is illustrated in Tables 2 and 3
- *Social pillar: Customer health: Acid index (mgKOH/g).*
  - o Acid value (or neutralization number or acid number or acidity) is the mass of potassium hydroxide (KOH) in milligrams that is required to neutralize 1 g of chemical substance. This is required to evaluate product health.
- *Reusability of materials.*
  - o The percentage of the value obtained from recycled products to retailed price.

Table 10 illustrates the magnitude of the above criteria approximated for different products. These criterias are simultaneously considered with economic objectives, pointed previously.

5.2. Results of the proposed methods

This section provides the detailed results obtained by proposed algorithms. All the experiments were executed in MATLAB 2012 and run on an Intel Core i3 2.10 GHz, HP Pavilion g6 at 4 GB RAM under a Microsoft Windows 10 environment. Using the proposed Lagrangian relaxation approach with sub-gradient optimization, after solving each objective function independently under the problem constraints, the optimum values of objective functions were obtained as $Z_1^* = 62349.70$, $Z_2^* = 586.82$, and $Z_3^* = 123.27$. Now based on the relative importance of the objective functions, the best compromise solution to the problem is addressable. The decision-makers (DMs) relative importance in the studied supply chain was determined as $W_1 = 0.50$, $W_2 = 0.25$, and $W_3 = 0.25$. The proposed heuristic algorithm converges the optimal solution after 8 iterations within 2 s, and the best compromise solutions were obtained as $Z_1 = 57406.03$, $Z_2 = 498.48$, and $Z_3 = 41.33$.

Solving the problem using GA with tuned parameters: i.e. $N_{pop} = 15$, $P_c = 0.7$, and $P_m = 0.25$, the results showed that each generation of the algorithm lasts about 1.7 s and GA was unable to converge the optimal solution in an acceptable time. The best solution over 500 generations (850 s) was obtained as $Z_1 = 57289.3$, $Z_2 = 486.2$, and $Z_3 = 41.25$ and had an error gap of 2.6%. The authors also solved the problem by SA with tuned parameters: i.e. $T_0 = 200$, $T_f = 0.01$, $\alpha = 0.97$ and $N = 10$. Similarly, the proposed SA was unable to converge the optimal solution in an acceptable time and its best solution over 326 iterations (521 s) was obtained as $Z_1 = 57163$, $Z_2 = 489.2$, and $Z_3 = 40.61$ and faced an error gap of 3%. Table 11 denotes the detailed results of the proposed methods.

5.3. Sensitivity analysis

The authors investigate five scenarios (S_1, S_2, S_3, S_4, and S_5) concerning the different relative importance of objective functions. Table 12 shows the detailed results of the considered scenarios.

Fig. 7(a) to 7(c) illustrate the sensitivity of objective functions against changes in the average demand. Unlike the former case, the effect of demand changes on objective functions has no clear pattern. The first product has an irregular effect on Z_1. Alternating its demand from −30% to 10% harms Z_1; nevertheless, increasing its demand by more than 10% and causes a positive growth in Z_1. For second and third products (n_2 and n_3 respectively), any increase or decrease changes make Z_1 worse. On the other hand, the fourth and fifth products have a direct positive impact on Z_1.

According to Fig. 7(b), regarding the second objective, it is clear that except for the fourth product, i.e. n_4, the rest of the products have a direct impact on Z_2. For the third objective, changing the mean rate of demand for the first and second products has a direct positive impact on the objective function while the fourth and fifth products illustrate a negative impact. This behavior routes back to the prices of products. Moreover, the third product illustrates an irregular impact on Z_3.

6. Implications and conclusion

Generally speaking, the issue of sustainability and its considerations in the world is an increasing trend that is observed in developing different managerial and economic models. The newsvendor problem is one of the problems in economic and management literature that research works studied in determining optimal inventory and ordering levels of transactions among a central warehouse and a single or a set of retailers. *Theoretically*, in this paper, the newsvendor model was developed considering sustainability criteria based on the TBL model. The classic newsvendor model of optimizing supplier-retailer payoff was considered to illustrate the economic perspective of sustainability. However, in this research other objectives were formulated to model the social and environmental pillars of sustainability. After analyzing pertinent research works, in the vast majority of cases, the scholars only focused on the economic pillar. Besides, only a few research works focused on two and all three (e.g. Tsao et al., 2017) pillars. Therefore, in this research, a multi-objective non-linear constrained model was developed to cover the research gap.

To solve the formulated model, a compromise programming approach was hybridized with Lagrange relaxation and sub-gradient optimization to solve the proposed model. Note that only a few research works focused on developing and designing new algorithms for solving multi-product newsvendor problems (e.g. Mohammadivojdana and Geunes, 2018; Murarkaa et al., 2019). To compare the obtained results, the proposed method was also solved via a genetic algorithm. Results illustrated that both in terms of optimality and solution time, the proposed method had an extraordinary performance compared to GA and SA. The optimality of a solution obtained by the proposed method was guaranteed since was emanated from solving equations of KKT conditions. Furthermore, a real-world case study was examined in the FMCG industry that formulated the transactions among the central warehouse of a manufacturer with its regional warehouses. In this regard by gathering real historical data for product demand, some statistical distributions were fitted and the cost parameters were approximated. Applying real-world data for newsvendor problems is rarely investigated (e.g. Guo et al., 2019; Huber et al., 2019) indicating that employing these models, in reality, is difficult. The majority of previous research works only validated and verified their proposed models by numerical examples. Eventually, formulating and solving the model, the optimal ordering policy was determined in this research. Moreover, a sensitivity analysis was applied to illustrate the behavior of the model against changing its parameters.

Practically, by comparing the obtained results with the classical newsvendor model, it is clear that without considering social and environmental objectives, the single economic objective loses at least 0.76% and at most 14.1% of its achievements by a trade-off with sustainable criteria. It is deduced that in industries with a lower emphasis on social and/or environmental pillars, more weight is assigned to the economic pillar and the proposed method achieves a value close to the classic newsvendor model with a single economic objective. However, growing the emphasis and importance of social and environmental pillars, more weights should be allocated to these pillars that will decrease the optimal value of the economic objective. This tradeoff is an inevitable consequence of multi-objective problems that justifies by the global tendency toward sustainability. Furthermore, according to the obtained results, it is comprehended that by increasing the importance weights of social and environmental criteria, the order magnitude of products with higher performance in these criteria tends to be increased while other product orders are decreased. The authors believe that a combination of three probabilistic distribution, sustainability pillars, multi-objective model, and multi-product newsvendor problem has not been previously considered by other scholars. Besides, the authors have developed and designed a new algorithm for this matter instead of employing existing ones. However, in this research, the proposed model is designed based upon a single-period inventory and ordering system. Hence, future studies should focus on developing the proposed method for a multi-period time horizon. Besides, the proposed model is based on a centered/single warehousing structure and multi centers are not considered. Thus, the next research works should focus on several central warehouses that cooperate or compete in satisfying regional warehouse demand. Furthermore, in this case, the routing of vehicles should be investigated along with the multi centers. In this regard, designing coordination contracts should also be studied by considering sustainability criteria in the context of the newsvendor model. Beyond the above suggestions for future studies, scholars also need to focus on the development of the proposed model considering inspection errors and the rate of defects in ordering decisions.

CRediT authorship contribution statement

Seyed Hossein Razavi Hajiagha: Conceptualization, Methodology, Writing – original draft, Writing – review & editing, Supervision, Project administration. **Saeed Alaei:** Conceptualization, Software, Writing – original draft, Writing – review & editing, Supervision, Project administration. **Hannan Amoozad Mahdiraji:** Writing – original draft, Writing – review & editing, Supervision, Literature review.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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