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Multi-objective optimization modelling of sustainable green supply chain in inventory and production management

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Abstract The ever increasing pressure to conserve the environment from global warming cannot be overemphasized. Emission from the inventory and production process contributes immensely to global warming and hence, the need to device a sustainable green inventory by the operational managers. In this paper, a multi-item multi-objective inventory model with back-ordered quantity incorporating green investment in order to save the environment is proposed. The model is formulated as a multi-objective fractional programming problem with four objectives: maximizing profit ratio to total back-ordered quantity, minimizing the holding cost in the system, minimizing total waste produced by the inventory system per cycle and minimizing the total penalty cost due to green investment. The constraints are included with budget limitation, space restrictions, a constraint on cost of ordering each item, environmental waste disposal restriction, cost of pollution control, electricity consumption cost during production and cost of greenhouse gas emission in the production process. The model effectiveness is illustrated numerically, and the solution obtained to give a useful suggestion to the decision-markers in the manufacturing sectors.

1. Introduction

There are pressing need to conserve our environment, the increase in awareness, expectations, and demand by customers, coupled with stringent carbon policies called for a reduction in carbon emissions along our supply chain path to the inventory we hold. The dynamicity of stock level excess and shortage

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levels requires optimization for the inventory management in the entire green supply chain network. Certain gases in the earth's surfaces prevail others, thereby creating global warming, which is of concern to all stakeholders. Carbon dioxide (CO_2) emission, methane and nitrogen oxides, contribute immensely to global warming. Human actions, such as industrialization and burning of fossil fuel, transportations, deforestations, and electricity generation, are the significant causes of greenhouse gas emissions (GHGs). These can be seen from Figs. 1–3. GHGs emissions are increasing at an alarming rate. In 2011 alone, global emissions are higher than those in 1850 by 150 times [1]. The global economy depends mostly on fossil fuel for industrialization; hence GHGs emissions cannot be avoided entirely; instead, the emission rate can be reduced significantly to mitigate global warming. The impacts of global warming are visible; hence international organizations, governments, industries and individuals recognised the necessity for reducing global CO_2 emissions. Consequently, policies related to emissions reduction, such as environmental management systems, emissions trading schemes, and green taxes are proposed and implemented gradually to mitigate the process. Sustainable green supply chain (SGSC) requires having a network of minimized order quantity, transportation and production of CO_2 emissions, reduced environmental impacts as well as emission cost and other logistic activities related to resource reduction such as investment cost on green equipments in an optimal fashion.

Green supply chain (GSC) is the most required by industries and business-oriented firm today. The top managers of various organizations make a crucial decision towards the successes or otherwise of their organizations. They are often referred to as decision-makers (DM) in that regards. Emissions in retail industries such as manufacturing, packaging, and transportations amount to 80–90 per cent of the total carbon footprint [2]. Industrial transportation, manufacturing, storages, and warehousing contributes immensely in GHGs emission in the supply chain process of the inventory. Ordering or set up costs, production costs and warehousing activities are the main phases for a production-inventory system of any firm. Under the regulation policies of carbon emission, a firm needs to optimally reset its decision policies for the productions, inventory and warehousing in order to reduce emissions [3]. A firm can significantly reduce emission by investing in greener inventory warehousing and production. The significant challenges facing DMs is how to accurately measure the information needed for the industries to flourish shortly and to stand the competitive environment; hence the need to address these costs related to emissions by formulating viable inventory policies. The uncertainty in business fluctuations and its complexity resulted in the inability for DMs to forecast the future information parameters about the business correctly. These input parameters are independent factors but can lead to failure of the entire system if not well managed. However, the DMs might have a rough knowledge on most of the independent factors based on experience and records in the system; therefore they can be able to express these uncertainties in their domain using the concept known as fuzzy set theory developed by [4]. This concept allowed the DMs to represent their ideas or intuitions with different fuzzy numbers (triangular or trapezoidal) as intuitionistic fuzzy set (IFS) to enable them address the ambiguities in their decision-making process [5]. One of the essential objectives facing the researchers is to design an inventory network that considers green and social issues and can minimize the costs simultaneously [6]. Incorporating green strategies and sustainability in logistics can be primary to addressing these problems. In a broader vision, these can provide green products and services for customers, and minimize the cost of environmental impact on the overall logistics of an item's flow.

The trucks and lorries known as heavy duties which tranships goods and services from one location to another, do exi-

Fig. 1 Emission from transportation activities.

Fig. 2 Emission from industrial activities.

Fig. 3 Emission from deforestation.

bits smokes which accumulate in the sky and contributes to the global warming. A typical example is shown in Fig. 1.

The manufacturing industries also uses a heavy machineries for producing different kind of materials, goods and services ranging from lighter to heavier which uses gasoline, petrol and ethanol among others during the production/manufacturing runs. This machineries exibits a very substantial amount of GHGs emissions which in turn affect the environmental well-being of the livingthings as can be seeing in Fig. 2.

Human activities such as burning of firewoods, forest trees (deforestation) affect the environment immensely as it emits gaseous substances in the atmosphere, kill organisms and create a global warming. This is a serious issue that concern everyone to provide a lasting solution towards curbing its continuation. An example of deforestation is pictorially represented in Fig. 3.

1.1. Paper organization

The rest of this paper is organized as follows: In Section 1, the introduction and overview of the study is provided. In Section 2, various related works are reviewed, research gap and contributions are surfaced. Section 3 contains multi-objective green inventory model formulation. The solution procedure for the model is described in Section 4. Section 5 provides a case study and the proposed model is illustrated by an example numerically. Also, a sensitivity analysis carried out on the solution to ascertain its validity range, while in Section 6, the results are discussed and analyzed. The article is concluded in Section 7 and suggested direction for further investigation.

2. Literature review and research gap

This section will discuss the related work in green supply chain (GSC), and inventory and production management. It will also provide an existing gap which informed this reserach work along side its contributions to the field of sustainable management for GSC inventory related issues. The next section review the literature.

2.1. Literature review

Many authors in different field of human endeavour developed and used various approaches to addressing different aspects in the area of inventory/supply chain management. For instance, IFS theory approach has been used to address different inventory problems [8,7]. Possibility, necessity, and credibility measures are used as a new approach to solve intuitionistic fuzzy optimization problems [9]. It has also applied in manufacturing, inventory models with shortages to obtain pareto optimal solutions [10]. Planning in a supply chain management (SCM) for production–distribution under imprecise environment has been discussed [11]. A scoring function, α and β cuts are use to defuzzify a triangular intuitionistic fuzzy number (TIFN) as a new approach to obtaining a solution [12]. Multi-objective IFS optimization was studied and documented [13–15] and many others. Inventory control-related models were developed and used by many authors. These are by way of extending the classical economized order quantity (EOQ) proposed by [16]. For example, A mathematical programming model was formulated for minimizing a production cost and delivery time in supply chain management [19,20]. Geometric programming was used in formulating a lot-size multi-item inventory problem with deterministic varying cost [17]. Multi-item inventory model formulated under a fuzzy environment, in which the model considered a lead time with demand dependent, production cost and set-up cost parameters as fuzzy [18]. A comprehensive analysis and evaluation for articles published by Journal of cleaner production in reverse logistics and closed-loop supply chains have been carried out by [21]. A similar review based on structural equation and fuzzy modelling in GSC was studied and documented [22–24]. Supplier's collaboration capacity towards cleaner production has been studied as a multi-dimensional in supply chain management [25]. A multi-objective approach is used to optimize the underground reservours for energy and freshwater extraction [26]. Multi-objective programming have been used in evaluateing the optimal green suppliers considering both environmental and economic issues [27]. An optimal order allocation of products in the supply chain network (SCN) was studied as a bi-level and multi-objective programming [28,30]. An integrated multi-objective optimization and fuzzy goal programming approaches have been applied in sustainable development goals [28–32]. Inventory and supply chain models are also studied as a multi-objective problem under LR and intuitionistic fuzzy environment [33–35]. The ultimate goal of inventory is to have an informed policy about the quantity to be ordered and when to order at an economized cost. A deterministic inventory model was considered, optimizing both the holding and ordering cost simultaneously [36]. Fractional programming was used to address the non-quasi-convex holding-and-ordering cost of an inventory model [37]. A single EOQ inventory model where the demand rate of customers is dependent on the stock and price of the vendor was considered and studied [38]. An exponential, normal, and uniform lead-time-demand and fuzzy cost function was considered to formulate a stochastic inventory model and solved by Zimmermann technique and fuzzy intuitionistic optimization technique respectively [39]. An inventory model for production lot-sizing problem having a deterioration and demand rate was developed as fuzzy under permissible payments delay and a finite production rate [40]. Recently, inventory with price dependent demand, partial backlogging, and partial trade credit policy has been considered and partial differential equations applied in supply chain and inventory control [41–43]. A multi-objective optimization-based neural network modelis proposed to tackle fashion industry problem of short term replenishment and solved by an evolutionary algorithm technique called nondominated sorting adaptive differential evolution algorithm [44]. A model of an inventory in which the demand and different cost were regarded as fuzzy numbers and used different membership function of IFP to obtain the pareto optimal solution was considered [9]. The work was extended to considere an EOQ model of inventory with two imperfect quality items [45]. A block replacement and periodic review policies for inventory was applied to optimize multi-unit systems under deteriorating spare part jointly [46]. The expected cost of transhipment in supply chain network was optimized using mixed-integer programming technique [47]. An IFO algorithm was developed to solve inventory model with certain and uncertain parameters [7]. Metaheuristic approach was used to determine the optimal inventory policy by optimizing the service level and total cost simultaneously. It has been also applied in pharmaceutical and citrus supply chain network [48–51]. Heuristic modelling for sustainable procurement and logistics have been applied in a supply chain using the concept of big data[52]. A Multi-objective optimization for inventory model were formulated considering a multi-products without shortages and used fractional programming concept to obtain the optimal solutions to the inventory problem [53,54]. A fuzzy MOP for inventory model with joint replenishment of deteriorating items which maximize the returns on investment was developed [55]. A multiple objective decision-making inventory model was designed using the concept of fuzzy rough theory [56]. The concept was extended according to uncertainty theory [57]. A multi-objective and economic production quantity model under reliability and flexibility environment with fuzzy random demand was developed and used [58–60]. Some strategies to reduce GHGs emissions in a green inventory set up was described mathematically in a lighter form [61]. An economic production quantity model with multiple imperfect items was proposed, considering the fixed and variable pollution cost in an ecofriendly environment [62,63]. A dual model of multi-objective linear-fractional inventory under fuzzy environment without considering the environmental (GHGs) and social aspect of it was documented[33]. The demand for the product has an important issue in the inventory as well as supply chain analysis. Also, the price has a great effect on demand, i.e., the price of the product increase then demand will decrease and vice versa. The demand for the product is not always fixed. In the existing literature, a different format of the demands is available. Similar recent works are documented[64–75] among others.

Nowadays, GHGs emission is an important issue worldwide. Every production firms need to control the emission rate to save the environment as well as human civilization. Due to increasing the awareness program of GHG emission, currently, researchers are focused on studying the control of GHG emission in the supply chain as well as an inventory system. They are trying to introduce an effective model to control the emission rate. An inventory model with a focus on environmental issue has been studied[76]. They have given the priority of the environment and studied a new concept in the area of inventory control. The sustainability concept have been introduced in the area of inventory control [77]. They developed an inventory model focused on sustainability. A sustainable inventory model under uncertainty was proposed [78]. A sustainable EOQ model was developed with a focus on both economic and environmental issue [79]. An EQO model for spare parts was proposed under uncertainty [80]. A carbon-constrained inventory model where demand depends on carbon emission rate also proposed by [81]. An EOQ model with the approach of extended energy studied [82]. The impact of imperfect quality items were examined [83]. A reverse logistics inventory model with an environmental perspective has been investigated [84]. Sustainable supply chain system with the sharing of information has been proposed [85,86]. A stochastic non-stationary inventory system has been proposed [87]. Trade credit and carbon cap policy in lot sizing system studied by [88], while the optimal production to curb the carbon emissions under low subsidy of cap and trade policy has been studied by [89]. An integrated supply chain system proposed by [90], where they focused on an economic and environmental issue. Manufacturing strategy has been investigated along with environmental issue [91]. A study on sustainable supply chain and integrated concept on sustainability reported in [92]. In this connection, we may refer some recent works such as [64–96] among others. The next section provide the research gap and contributions of our work.

In Table 1, present a compact illustration of review of some related literature to the proposed area of research.

2.2. Research gap and contributions

Over the years, few kinds of research work has been carried out on the multi-objective inventory and supply chain problems. For instant, a study conducted on inventory problem where a profit was maximized and inventroy holding cost minimized using multi-objective approach [54]. Inventory production problem studied as a multi-objective, using fuzzy and intractive programming to minimize total cost of transpotation and delivery time of the inventory level considering space availability [97]. They further studied a vendor selection problem in supply chain management to minimze net ordering price, rejected items, and late delivery [28]. A multiobjective inventory problem under intuitionistic environment was studied [33], extending the work of [54]. A decentralized multi-objective sustainable supply chain model formulated under intuitionistic environment [34]. Recently, vendor selection problem in supply chain mangement under LR-Type fuzzy environment has been studied [35]. Most of the authors formulated the problem as a multi-objective optimization to either maximize the profit or minimize the holding costs of inventory or both without given attention to the environmental issues. Also, deteriorations in demand were not considered by these papers. However, our proposed work integrates the environmental issues such as the GHGs emission cost, cost of environmental polution, cost of waste disposal, carbon dioxide emission due to transportation of goods from plants to warehouses, cost of electricity consumptions during production and inventory management among others. All in an attempt to sustain the environmental safety and ensure greener supply chain in the inventory and production management. Additionally, this work considered the deteriorations in demand to enable the decision-makers to have more insight and understand its effects throughout the supply chain network. Considering carbon-emissions cost, environmental pollution cost, waste disposal, electricity consumption, and the profit generated in a production and inventory firm simultaneously is a challenging task. However, the proposed work overcome these challenges by minimizing the total expected cost of GHGs emissions, the environmental cost for waste disposal, production and inventory holding cost and optimizes the profit to the ratio of backorder quantity simultaneously. It has also considered different objectives related to the waste produced by the inventory system per cycle and the total penalty cost incurred in the system. With the proposed work, all the cost related issues and the profit are optimized simultaneously. In the next section, we present the multi-objective fractional green inventory discussion and the model formulation.

3. Multi-objective linear fractional green inventory and production model

Green inventory entails keeping sufficient stock of desired goods and services. The inventory guarantees the smooth running of business activities as well as production systems in an environmental friendly fashion by way of optimizing the GHGs such as green technology investment, green setup cost, green procurement cost, holding cost, green logistic cost, pollution control cost, CO_2 emission, green packaging cost, and waste produced by the inventory system among others. The dynamicity of excess and shortage of stock level couple with environmental hazards called for optimization in the supply chain of green inventory and production management. According to [98], the method of greener productions shifts industries from red ocean strategies (low price market competition) to blue ocean strategies (new competition opportunities). In this paper, we are formulating GSC for inventory and production management as a multi-objective linear fractional problem with variant objectives. The aim is to optimize the carbon-related emission costs at various stages of production and inventory period, electricity consumptions costs during production and warehousing of inventory, the yearly profit per quantity ordered, and the holding cost of inventory per year per quantity ordered respectively. The next subsection provides the undelying assumptions for the model formulation as well as the nomenclature/symbols used in the mathematical model building accordingly.

Table 1 Summary of some literature, based on various assumptions related to the proposed model.

Reported works	Multi items	Multi-objective	Objective type max/min	Backordered quantity	GHGs emission cost	Deteriorations in demand	Environmental pollution cost	Electricity consumption cost	CO_2 emission from transportation	Optimization technique(s) applied
Datta [3]	×	×	min & max	×	√	×	×	×	√	Initial value problem
De et al. [7]	×	√	min	√	×	×	×	×	×	Intuitionistic Fuzzy programming
De and Sana [8]	√	√	min	×	×	×	×	×	×	Linear Prog., Intuitionistic Fuzzy programming
Chakraborty et al. [9]	×	√	min & max	×	×	×	×	×	×	Intuitionistic Fuzzy Chance Constrained
Chakrabortty et al.[10]	√	×	min	×	×	×	×	×	×	Intuitionistic fuzzy programming
Garai et al. [11]	√	√	min & max	×	×	×	×	×	×	Intuitionistic fuzzy T-set
Nagoorgani and Ponnalagu [12]	×	×	max	×	×	×	×	×	×	Triangular Intuitionistic Fuzzy number
Hariri and Abou-El-Ata [17]	√	×	min	×	×	×	×	×	×	Geometric programming
Das [18]	√	×	min	×	×	×	×	×	×	Geometric Programming, Fuzzy Programming
Sabri and Beamon [19]	√	√	min	×	×	√	×	×	×	Differential equation
Fakhrzad and Goodarzian [23]	√	√	min & max	×	√	×	×	×	√	MILP, Imperialist Competitive Algorithm
Fakhrzad et al. 2018 [24]	√	√	min & max	×	√	×	√	×	√	Metaheuristic
Gupta et al. [28,97]	√	√	min & max	×	×	×	×	×	×	Fuzzy Programming
Mohammed et al. [30]	√	×	min	×	×	×	×	×	×	Special case of Linear programming
Ali et al. [33]	√	√	min & max	√	×	×	×	×	×	Intuitionistic fuzzy programming
Kamal et al. [34]	√	√	min & max	×	×	×	×	×	×	Intuitionistic fuzzy programming
Ali et al. [31,35]	√	√	min & max	√	×	×	√	×	×	Trapezoidaic Fuzzy Number
Sadjadi et al. [36]	√	√	min & max	×	×	×	×	×	×	Fuzzy programming.
Chen [37]	√	×	min	√	×	√	×	×	×	Fractional programming algorithm
Khanra et al. [38]	√	×	min	×	√	×	√	×	×	Function Method, Interior Penalty Method
Kundu and Chakrabarti [40]	√	×	min	×	×	√	×	×	×	Triangular fuzzy number
Das et al. [41]	√	√	min	√	×	√	×	×	×	Taylors series approximation technique.
Zhang et al. [43]	√	×	max	×	×	×	×	×	×	Partial differential equations.
Jiang et al. [46]	√	√	min &	×	√	×	√	×	√	Intuitionistic fuzzy programming

Table 1 (*continued*)

Reported works	Multi items	Multi-objective	Objective type max/min	Backordered quantity	GHGs emission cost	Deteriorations in demand	Environmental pollution cost	Electricity consumption cost	CO_2 emission from transportation	Optimization technique(s) applied
			max							technique.
Bhaya et al. [45]	√	×	min	×	√	×	×	×	×	Intuitionistic fuzzy programming technique.
Tiwari et al. [70]	√	√	min & max	√	×	√	×	×	×	Differential equations: boundry condition
Rafiei et al. [47]	√	√	min	√	×	×	×	×	×	Mixed Integer Programming, Genetic algorithm
Goodarzian et al. [49,50]	√	√	min & max	×	×	×	√	×	×	Metaheuristic, Fuzzy programming
Fattahi et al. [48]	√	√	min & max	√	×	√	×	×	×	Metaheuristic
Fakhrzad and Goodarzian [51]	√	√	min & max	×	×	×	×	×	×	Metaheuristic
Kaur and Singh [52]	√	√	min	×	√	×	√	×	√	Mixed Integer Linear and Non Linear Program
Kumar & Dutta and Dutta & Kumar [53,54]	√	√	min & max	√	×	√	×	×	×	Fuzzy goal programming
Wee et al. [55]	√	√	max	×	×	√	×	×	×	Differential evolution, Fuzzy programming
Shah and Soni [58]	√	√	max	√	×	√	×	×	×	Metaheuristic
Goodarzian et al. [59]	√	√	min & max	×	×	×	×	×	×	Metaheuristic
Goodarzian and Hosseini-Nasab [60]	√	√	min & max	×	×	×	×	×	×	Possibilistic programming, Fuzzy programming, Metaheuristic
Bhattacharyya and Sana [61]	√	√	min & max	×	√	×	√	×	×	Sequential Unconstrained Maximization Technique
Mukhopadhyay and Goswami [63]	√	×	min	×	×	×	√	×	×	Diffirential equations
Bhunia and Shaikh [66]	√	√	min & max	√	×	√	×	×	×	Differential equations
Ghoreishi et al. [67]	√	√	min	√	×	√	×	×	×	Differential equations
Hovelaque and Bironneau [81]	√	√	min & max	√	√	√	×	×	×	Differential equations
Kazemi et al. [83]	√	√	min & max	×	√	√	×	×	×	Partial Differential equations
Lee et al. [95]	√	√	min	×	√	×	×	×	×	Differential equations
Present work	√	√	min & max	√	√	√	√	√	√	Fractinal programming, Fuzzy Programming, Weighted FGP

3.1. Assumptions and numenclature for the model

For every scientific abstraction of the real world, there exist symbols or variables used for modelling purposes which must be defined for a proper understanding of the situations together with certain assumptions under which the formulated model(s) hold, these are explain in Sections 3.1.1 and 3.1.2 below:

3.1.1. Assumptions

The following items are assumed in our model

1. It is a Multi-item inventory model
2. It has an infinite time horizon
3. It has only one cycle period
4. The rate of demand is independent of the price for the item.
5. No lead time is allowed
6. No shortages are allowed.
7. Deterioration is considered with a constant rate of α_i.
8. No quantity discount is allowed.
9. Inventory holding cost and purchasing price are supposedly known and persistent.
10. Production rate is finite, constant and higher than the demand rate
11. Reducing pollution and disposal are the focus of waste management.
12. Reducing carbon-emission and associated features in the inventory and production
13. Per unit production quantity of operating and Maintainance cost of pollution

3.1.2. Nomenclature

It has been the practice scientifically to define some notations used in model building for easy understanding and clear presentaions. Table 2 present the notations used in our model.

Table 2 Nomenclature.

Indices	Meaning
i	Index for item, $\forall\ i = 1, 2, \ldots, n$
Parameters	
B:	Total offered budget for all products/items
C_i:	Production cost per unit per item.
C_p:	Total pollution control cost for production run.
C_{om_i}:	Mentainance and operational cost for pollution control per unit of quantities produced
C_L:	Total inventory labouring cost
C_ω:	Total penality cost for a production run.
C_G:	Total cost of investment on green technologies.
C_{em_i}:	Unit cost of industrial emission associated with producing a unit of i^{th} item.
C_{ec_i}:	Unit cost of electricity consumption associated with producing and holding an inventory for the i^{th} item
C_{ve_i}:	Unit cost associated with vehicle emission during transhipment of goods to warehouses for the i^{th} item.
D_i:	Quantity demanded per unit time for the i^{th} item.
F:	Total accessible space for all products
f_i:	Space required per unit for the i^{th} item.
h_i:	Inventory holding cost per item per year for the i^{th} item.
k:	Stable cost per demand per item.
L_{c_i}:	Unit cost of labour for packing the i^{th} item in inventory.
M_{c_i}:	Unit cost of material used for packing the i^{th} item in the inventory.
n:	Number of products/items
O_i:	Unit oredering cost for the i^{th} item.
P_i:	Unit price for purchasing the i^{th} item.
Q_i:	Total ordering quantity of the i^{th} item.
S_i:	Unit price for selling the i^{th} item.
α_i:	Deterioration rate of the i^{th} item.
β_i:	Prportion of defective product per lot Q for the i^{th} item during the production run.
γ_i:	Proportion of demand return per item per production run ($0 \leqslant \gamma \leqslant 1$).
ω_i:	Unit cost of waste disposed to the environment per item.
θ_o:	Fixed pollution factor.

3.2. Model formulation

This section deals with the model formulation of the SGSC for inventory and production management and is sub-divided into two parts viz the objectives and the constraints parts.

3.2.1. Objective functions

This section explain the objectives of the model to be optimize and is made up of four equations. The first objective optimizes the profit generated by the inventory system. The second objective optimizes the inventory holding cost in the system; the third objective optimizes the waste produced by the inventory system per cycle and the fourth objective optimize the total penality cost that could be incurred in the system. The mathematical expressions of the objectives are given below:

$$Maximize\ Z_1 = \frac{\sum_{i=1}^{n}(S_i - P_i)Q_i(1-\alpha_i)}{\sum_{i=1}^{n} D_i - Q_i(1-\alpha_i))} \tag{1}$$

$$Minimize\ Z_2 = \frac{\sum_{i=1}^{n}\frac{h_i Q_i(1-\alpha_i)}{2}}{\sum_{i=1}^{n} Q_i} \tag{2}$$

$$Minimize\ Z_3 = \sum_{i=1}^{n} Q_i \omega_i [\gamma_i + \beta_i] \tag{3}$$

$$Minimize\ Z_4 = \sum_{i=1}^{n} Q_i [C_{em_i} + C_{ec_i} + C_{ve_i}] \tag{4}$$

3.2.2. Constrains

This section gives the account of the various conditions known as constraints or limitations, for which the objectives formulated in Section 3.2.1 are to be optimized simultaneously. They are comprises of eight equations (Eqs. (5)–(12)). Eq. (5) is the upper limit of the total investment, meaning that no matter what happens, the right-hand side should not exceed the amount invested in that regard (say B). Eq. (6) poses the limitation on the warehouse capacity, which implies that it can hold a certain number of the product only at a given time (say F). Eq. (7) is the upper restriction on the total waste to be disposed to the environment by the inventory system. Eqs. (8)–(10) restrict as minimum as possible the pollution control cost, the labouring cost, and CO_2 emission cost during the inventory production process. In contrast, Eq. (11) is the budgetary constraint on inventory ordering cost, and Eq. (12) is the technological constraints meaning that neither negative quantity nor negative ordering cost exists in the model. The constraints are mathematically represented as follows:

$$\sum_{i=1}^{n} P_i Q_i (1-\alpha_i) \leqslant B \tag{5}$$

$$\sum_{i=1}^{n} f_i Q_i (1-\alpha_i) \leqslant F \tag{6}$$

$$\sum_{i=1}^{n} Q_i \omega_i [\gamma_i + \beta_i] \leqslant C_\omega \tag{7}$$

$$\sum_{i=1}^{n} C_{om_i} \theta_o Q_i \leqslant C_P \tag{8}$$

$$\sum_{i=1}^{n} Q_i (L_{c_i} + M_{c_i}) \leqslant C_L \tag{9}$$

$$\sum_{i=1}^{n} Q_i [C_{em_i} + C_{ec_i} + C_{ve_i}] \leqslant C_G \tag{10}$$

$$kD_i - O_i Q_i (1-\alpha_i) \leqslant 0, \alpha_i > 0. \tag{11}$$

$$Q_i \geqslant 0 \ and \ O_i > 0, \ \forall i = 1, 2, 3, \ldots, n \tag{12}$$

Where

$\sum_{i=1}^{n} (S_i - P_i) Q_i (1-\alpha_i)$ *are profit related to ordering quantity*

$\sum_{i=1}^{n} \frac{h_i Q_i (1-\alpha_i)}{2}$ *represent the holding cost*

$\sum_{i=1}^{n} [D_i - Q_i (1-\alpha_i)]$ *represent the total back – ordered quantity*

$\sum_{i=1}^{n} Q_i (1-\alpha_i)$ *represent the total ordering quantity considering deterioration*

$\sum_{i=1}^{n} \frac{kD_i}{Q_i (1-\alpha_i)}$ *represent the total ordering cost, which can be express as :*

For product1 : $\frac{kD_1}{Q_1(1-\alpha_1)} \leqslant O_1 \Rightarrow kD_1 - O_1 Q_1 (1-\alpha_1) \leqslant 0;$

For product2 : $\frac{kD_1}{Q_2(1-\alpha_2)} \leqslant O_2 \Rightarrow kD_2 - O_2 Q_2 (1-\alpha_2) \leqslant 0;$

Similarly,

For the n^{th} *product :* $\frac{kD_n}{Q_n(1-\alpha_n)} \leqslant O_n \Rightarrow kD_n - O_n Q_n (1-\alpha_n) \leqslant 0;$

4. Solution procedure for MOLFIPP

The optimization problem formulated in Section 3.2 is a MOLFIPP and hence, requires a stepwise algorithm for obtaining the compromise solution. This section presents such a procedure. Many mathematical programming techniques are used to solve multi-objective optimization, one of which is goal programming (GP). More importantly, when the decision-makers have no precise knowledge about the future goals, fuzzy goal programming (FGP) proved to be a powerful technique in handling future aspirations for a decision-maker as it involves uncertainty in such scenarios. The stepwise procedures are summarized as follows:

- Step 1 The problem is formulated as a multi-objective fractional green inventory and production GP problem, taking into cognisant the parameters involved such as holding cost, purchasing and selling price, ordering cost, demand, green and social issues.
- Step 2 Solve the formulated problem in step 1 individually to obtain the optimal solution using any commercially available optimization packages such as GAMS, LINGO, LINDO, CPLEX and the like.
- Step 3 Convert the problem into FGP in light of model 13 by choosing the aspirational goals based on the optimal result in step 2 or the decision-makers given aspiration.
- Step 4 Construct the goals memberships in light of Eqs. (14), (15) or (16) as the case may be.
- Step 5 Standardize the membership function constructed in step 4 in light of Eq. (17).
- Step 6 Linearize the fractional problem in step 5 and 6 in light of Eq. (18) of Section 4.2, and solve the resulting deviational variables.
- Step 7 Determine the weight of each aspirational goal using the concept of Eq. (24).
- Step 8 Incorporate the weight into the admissible deviations and solve the resulting weighted fuzzy programming using Eq. (23).

The above solution procedure is depicted in Fig. 4. The next section discusses the FGP as it applies to our proposed model formulation and solution technique in detail.

4.1. Fuzzy goal programming

The theory of fuzzy set is a concept on which FGP is employed. Fuzzy sets described imprecise goals of a decision-maker. The goals sometimes are associated with the objective function or the constraints, and they can both reflect a weight with flexible achievement possibilities ranging between the value of zero and one. FGP allows decision-maker who cannot define goals in a precise manner to at least express them in weighting structure, which is not limited. Some decision is simple, while others are complicated. It is simple when there are precision and the precise cut of the boundaries in the environment. At the same time, it is very complicated when the environment is full of uncertainties and vagueness. The fuzzy set theory with imprecise boundaries can handle such vagueness

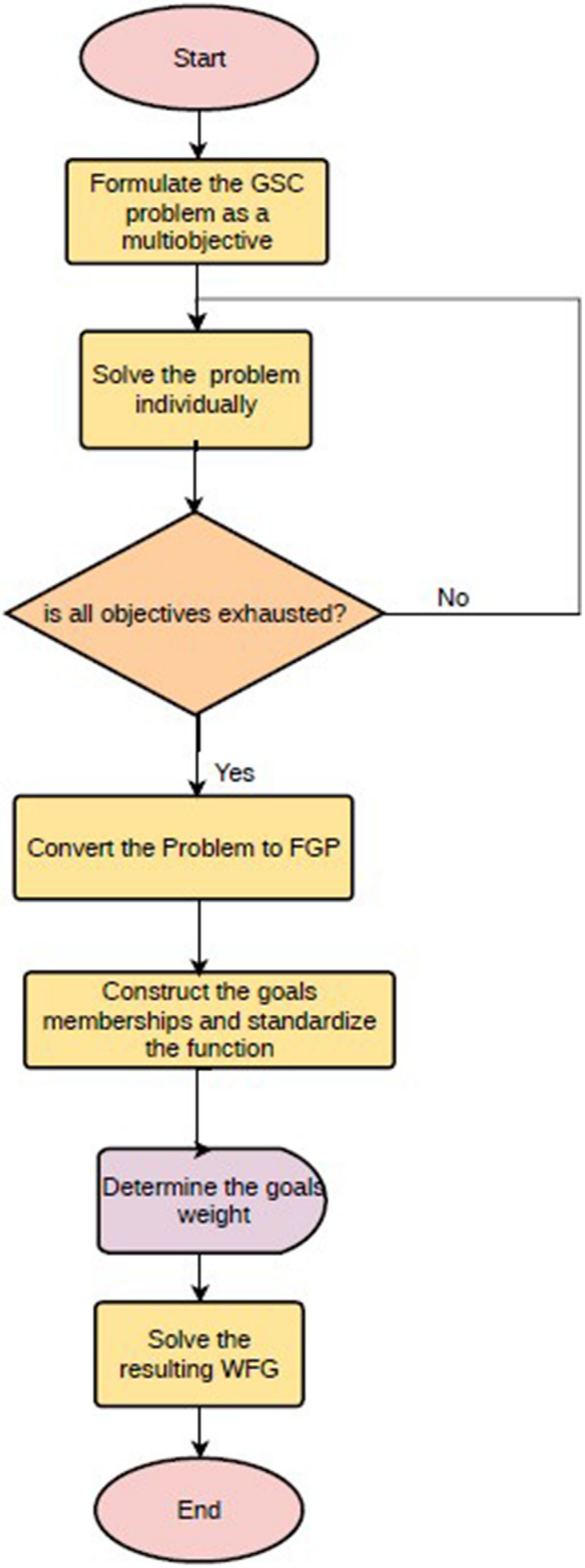


Fig. 4 Flowchart for the solution procedure.

and uncertainty property [4]. A fuzzy programming concept to solve a multi-objective DM problems in which both objectives and constraints of the problems considered to be a fuzzy set has been initially proposed[99]. The characteristic function (membership) in that set assigned some grades (real values) of membership laying between one and zero to each of the objective or goal of the DM. A generalized model for such type of problems (FGP) can be stated as

$$\begin{aligned} & Find \\ & X = (x_1, x_2, \ldots, x_n) \\ & such\ that: \\ & Z_k(X)\ (\succeq, \simeq, \preceq)\ g_k, \quad k = 1, 2, 3, \ldots, K. \\ & AX \leqslant b_i, \quad i = 1, 2, \ldots, m \\ & X \geqslant 0 \end{aligned} \tag{13}$$

where g_k represent vector of goals, b_i is the vector of resources available, and A is the technological coefficient. the symbol $\succeq$ is the fuzzy-max type, meaning that $Z_k(X)$ should approximately be more than or exact to the level of aspiration g_k, this implies that it can be satisfied by the DM even if it is less than g_k to a certain level. The symbol $\preceq$ stand for fuzzy-min, meaning that $Z_k(X)$ should be less than or exact to the level of aspiration g_k approximately, up to the allowable limit (tolerance). In contrast, the symbol $\simeq$ stand for fuzzy-equal implies that $Z_k(X)$ should be within the level of aspiration g_k, which means that it can be satisfied by the DM even if it is less than or greater than g_k to a certain level of tolerance. The k-th fuzzy objective is denoted by Z_k and the n-dimensional vector for decision variables is represented by X.

For multi-objective fuzzy goal programming, let g_k be the aspiration level set by DM for k-th objective value $Z_k(X)$. Thus, using the method developed by [99], the fuzzy-goal type $Z_k(X) \succeq g_k$ for a maximization problems (see Fig. 5), the characteristic membership is given as:

$$\mu_k(Z_k(X)) = \begin{cases} 1, & if\ Z_k(X) \geqslant g_k \\ \frac{Z_k(X) - L_k}{g_k - L_k}, & if\ L_k \leqslant Z_k(X) \leqslant g_k \\ 0, & if\ Z_k(X) \leqslant L_k \end{cases} \tag{14}$$

and for the minimization fuzzy-goal type $Z_k(X) \preceq b_k$ (see Fig. 6), the characteristic membership function is given as:

$$\mu_k(Z_k(X)) = \begin{cases} 1, & if\ Z_k(X) \leqslant g_k \\ \frac{U_k - Z_k(X)}{U_k - g_k}, & if\ g_k \leqslant Z_k(X) \leqslant U_k \\ 0, & if\ Z_k(X) \geqslant U_k \end{cases} \tag{15}$$

While the characteristics membership function for the fuzzy-equal goal of type $Z_k(X) \simeq g_k$ (see Fig. 7)) is given as:

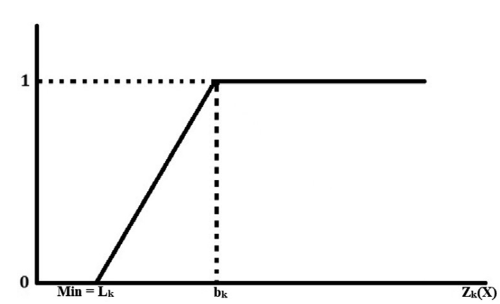


Fig. 5 Linear membership for fuzzy-goal type $Z_k(X) \succeq g_k$.

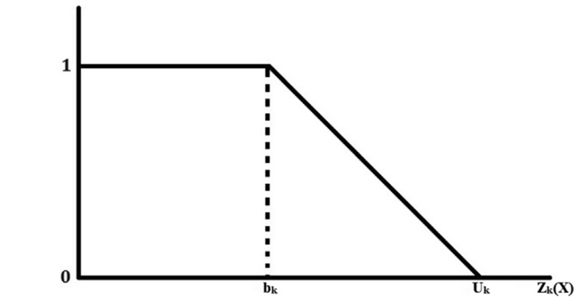


Fig. 6 Linear membership for fuzzy-goal type $Z_k(X) \preceq b_k$.

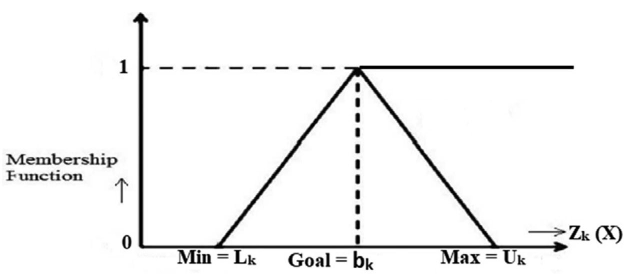


Fig. 7 Linear membership for the fuzzy-equal goal of type $(Z_k(X) \simeq g_k)$.

$$\mu_k(Z_k(X)) = \begin{cases} 0, & \text{if } Z_k(X) \leqslant L_k \\ \frac{Z_k(X)-L_k}{g_k-L_k}, & \text{if } L_k \leqslant Z_k(X) \leqslant g_k \\ \frac{U_k-Z_k(X)}{U_k-g_k}, & \text{if } g_k \leqslant Z_k(X) \leqslant U_k \\ 0, & \text{if } Z_k(X) \geqslant U_k \end{cases} \tag{16}$$

where U_k and L_k are the upper and lower limit of the aspiration levels g_k for the k-th goal as chosen by the DM.

The highest achievable level of the membership function in both cases is a unity, and hence its flexibility can be express as follows:

$$\begin{cases} \frac{Z_k(X)-L_k}{g_k-L_k} + \delta_k^- - \delta_k^+ = 1, \\ \frac{U_k-Z_k(X)}{g_k-L_k} + \delta_k^- - \delta_k^+ = 1, \\ \text{where } \delta_k^-, \delta_k^+ \geqslant 0, \text{ and } \delta_k^+ \cdot \delta_k^- = 0, \end{cases} \tag{17}$$

where the δ_k^+, δ_k^- denotes the under and over achievements of the aspirational level. It can be observe that Eq. (17) is a non-linear in nature and thus, can be linearize to ease the computational process as follows:

4.2. Multi-objective fractional programming

For the problem with k objectives, the fractional programming can be define as a function involving one or more ratio that are required to be optimize in some way. The multi-objective fractional programming can be stated as:

$$\begin{aligned} &\text{Optimize } Z_k(X) = \tfrac{a_k X + \aleph_k}{d_k X + b_k} \; k = 1, 2, \cdots, K; \text{ and } d_k X + b_k > 0; \\ &\text{Subject to}: AX \leqslant, =, \geqslant b, \; X \geqslant 0, \\ &X \in \mathbb{R}^n, b \in \mathbb{R}^m \text{where } a_k, d_k \in \mathbb{R}^n, \aleph_k, b_k \text{ are constant} \end{aligned} \tag{18}$$

Let the Fuzzy linear programming having m equality constarints and n fuzzy variables be define as

$$\begin{aligned} &\text{Optimize } \tilde{C}^T \otimes \tilde{X}; \text{ Such that}: \\ &\tilde{A} \otimes \tilde{X} = \tilde{b}, \\ &\text{where } \tilde{C}^T = [\bar{a}_j]_{1\times n}, \tilde{X} = [\bar{x}_j]_{1\times n}, \\ &\tilde{A} = [\bar{c}_{ij}]_{m\times n}, \bar{b} = [\bar{b}_i]_{m\times 1} \\ &\text{and } \bar{a}_j, \bar{b}_i, \bar{c}_{ij}, \bar{x}_j \in F(\mathbb{R}); \overline{X} \geqslant 0. \end{aligned} \tag{19}$$

Eqs. (18) and (19) are known as fractional and fuzzy linear programming, for which a DM sought to optimize his aspirational goals simultaneously under certain limitations.

Let $Y_k = \frac{1}{g_k - L_k}$ represent the fractional part of the Eq. (17), then the first part of it can be written as;

$$\begin{aligned} &Y_k Z_k(X) + \delta_k^- - \delta_k^+ = 1 + Y_k L_k, \\ &\text{In light of Eq. (18)}; \\ &\Rightarrow Y_k(a_k X + \aleph_k) + \delta_k^-(d_k X + b_k) - \delta_k^+(d_k X + b_k) = Y_k'(d_k X + b_k), \\ &\text{where } d_k X + b_k \text{ is the admissible deviation constant and } 1 + Y_k L_k = Y_k', \\ &\text{this } \Rightarrow C_k X + \delta_k^+(d_k X + b_k) - \delta_k^-(d_k X + b_k) = G_k, \\ &\text{where } C_k = Y_k a_k - Y_k' d_k, \text{ and } G_k = Y_k' b_k - Y_k b_k \end{aligned} \tag{20}$$

Letting $D_k^- and D_k^+ = \delta_k^-(d_k X + b_k)$ and $\delta_k^+(d_k X + b_k)$ respectively, Eq. (20) can be further express in linear form as

$$C_k X + D_k^- - D_k^+ = G_k\,. \tag{21}$$

Similarly, the second part of Eq. (17) can be linearized accordingly. The ultimate goal of this approach is minimizing the aspirational deviations, and that the overachievement and underachievement must be within the satisfactory threshold of the DM. And hence, δ_k^- *and* δ_k^+ can be minimized by minimizing the equivalent fractional deviations $D_k^-/(d_k X + b_k)$. If the goal is completely achieved, then $\delta_k^- = 0$, *otherwise* $\delta_k^- = 1$. Additional restriction can be introduced in the solution such that the $\delta_k^- \leqslant 1$, this can be given by

$$D_k^-/(d_k X + b_k) \leqslant 1;. \tag{22}$$

Eqs. (21) and (22) can be incorporated into the classical GP as documented in [31]. This can be seen as

$$\begin{aligned} &\text{Min } Z = \sum_{k=1}^{K} w_k^- D_k^- + w_k^+ D_k^+ \\ &\text{Subject to}: \begin{cases} C_k X + D_k^- - D_k^+ = G_k \\ AX \leqslant b_k, \\ X \in \mathbb{R} \geqslant 0, \\ D_k^-, D_k^+ \geqslant 0, k = 1, 2, 3, \ldots, K \end{cases} \end{aligned} \tag{23}$$

Here, the goal typically is a weighted fuzzy whereby the individuals $w_k^- \geqslant 0$, and can be computed from Section 3.2 as

$$w_k^- = \begin{cases} \frac{1}{g_k - L_k} & \text{if fuzzy goal } Z \text{ is} \preccurlyeq \text{type} \\ \frac{1}{U_k - L_k} & \text{if fuzzy goal } Z \text{ is} \succcurlyeq \text{type} \end{cases} \tag{24}$$

5. Case study

A Nigerian firm is into production and inventory management of some items (name withheld for an ethical reason). Items are manufactured in the production side and transported in trucks to the warehouse where they are kept and hold as inventory for subsequent supply to the customers on demand. The process involves purchasing some raw materials for production. It also consumes electricity during the production run, utilization of both skilled and unskilled labour forces for operational, on and offloading of finished items onto the trucks, and packing and arrangement in the warehouse to minimize available space, and finally sell out to the demanding customers. All these activities have some associated costs and environmental implications that are variant and hence, the firm must operate within the confinement of budgetary allocations, space requirements and environmental regulations amongst others. Also, a backed-order quantity of items may be experiencing due to deterioration and defectiveness of items during a production run. The sole aim of the firm's management is to realize an optimal possible profit, minimize all possible costs in the system, and at the same time remain viable in the business domain. Therefore, the need to optimize the entire supply chain network. In doing so, the sustainable inventory and production policy may be formulated within which the management will rest assured for continuity in business even if the demands fluctuate to a certain level which is a usual norm in every sector of businesses. As practice demands, such firms usually keep track of demands for their customers and monitor patronage throughout a financial year, and give out financial rewards and certificates as a motivation in order to maintain the goodwill of the customers.

5.1. Numerical solution

The MOLFIPP formulated in Section 3.2 is demonstrated considering four-item inventory and production problem. The information in Table 3 in light of the case study discussed in Section 5 is used as input parameter values, and the multi-objective model is expressed as follows:

$$Maximize\ Z_1 = \frac{100Q_1 + 60Q_2 + 35Q_3 + 30Q_4}{2900 - 0.8Q_1 - 0.6Q_2 - 0.7Q_3 - 0.4Q_4} \tag{25}$$

$$Minimize\ Z_2 = \frac{24Q_1 + 24Q_2 + 31.5Q_3 + 14Q_4}{Q_1 + Q_2 + Q_3 + Q_4} \tag{26}$$

$$Minimize\ Z_3 = 4Q_1 + 7Q_2 + 9Q_3 + 4Q_4 \tag{27}$$

$$Minimize\ Z_4 = 565Q_1 + 974Q_2 + 805Q_3 + 1055Q_4 \tag{28}$$

Subject to the constraints

$$3125Q_1 + 3650Q_2 + 2200Q_3 + 3900Q_4 \leqslant 4500000 \tag{29}$$

$$3.2Q_1 + 3.6Q_2 + 2.8Q_3 + 1.2Q_4 \leqslant 15000 \tag{30}$$

$$4Q_1 + 7Q_2 + 9Q_3 + 4Q_4 \leqslant 5150 \tag{31}$$

$$6Q_1 + 4.5Q_2 + 9Q_3 + 6Q_4 \leqslant 5000 \tag{32}$$

$$90Q_1 + 50Q_2 + 55Q_3 + 75Q_4 \leqslant 47000 \tag{33}$$

$$565Q_1 + 974Q_2 + 805Q_3 + 1055Q_4 \leqslant 360000 \tag{34}$$

$$12500 - 1280Q_1 <= 0; \tag{35}$$

$$25000 - 1050Q_2 <= 0; \tag{36}$$

$$18750 - 875Q_3 <= 0; \tag{37}$$

$$16250 - 460Q_4 <= 0; \tag{38}$$

$$Q_i \geqslant 0;\ \forall i = 1,2,3,4. \tag{39}$$

We coded Eqs. (25)–(39) into the LINGO software version 16.0 and solve the resulting nonlinear inventory model (NLIM). The optimal solutions for the individual objective functions alongside the optimal quantity values are shown in Table 4.

From the optimal Table 4, we can let the fuzzy aspirational levels for the four goals as $\tilde{g}_1 = 25,\ \tilde{g}_2 = 15,\ \tilde{g}_3 = 500,\ and\ \tilde{g}_4 = 80000,$ this values can

Table 3 Input parameters for production and inventory of four items.

Items	1	2	3	4
Holding cost per item/year, (h_i)	60	80	90	70
Purcahsing price, P_i	3125	3650	2200	3900
Selling price, S_i	3250	3750	2250	3975
Demand quantity D_i (units/year)	500	1000	750	650
Ordering cost per order, O_i	1600	1750	1250	1150
Required item space, f_i(sq. meter)	4	6	4	3
Operating and Maintenance cost per unit item, C_{omi}	20	15	30	20
Deteriorating rate α_i	0.2	0.4	0.3	0.6
Production cost per item/run, C_i	40	25	35	17
Proportion of demand return per item per production, γ_i	0.3	0.2	0.3	0.2
Waste disposal cost per item ω_i	8	14	15	10
Proportion of defective items β_i	0.2	0.3	0.3	0.2
Packaging Material Cost M_{ci}	50	30	25	35
packaging Labour Cost L_{ci}	40	20	30	40
Electricity consumption cost C_{eci}	150	212	320	500
Vehicle emission Cost C_{vei}	200	512	135	340
Emission Cost/production C_{emi}	215	250	350	215
Other parameters values	k = 25 θ_o = 0.3	C_p = 5000 C_ω = 5150	C_L = 47000 B = 4500000	C_G = 360000 F = 15000

NB: All the costs are in Nigerian currency and demands are in tones per year.

Table 4 Optimal individual solutions to the multiobjective problem.

Objectives	Q_1	Q_2	Q_3	Q_4	Solutions
$\mathbf{Z_1}$	450.6893	52.19868	21.42857	35.3261	19.9463
$\mathbf{Z_2}$	9.7656	23.8095	21.4286	297.6701	16.0153
$\mathbf{Z_3}$	9.7656	23.8095	21.4286	35.3261	539.8907
$\mathbf{Z_4}$	9.7656	23.8095	21.4286	35.3261	83222.08

serve in the FGP model as the upper limit for Z_1 objective since it is of maximization type and lower limits for the remaining objectives (Z_2, Z_3, Z_4) which are of minimzation categories. We can then assume their respective lower and upper limits as $L_1 = 10,\ U_2 = 30,\ U_3 = 2600,\ U_4 = 370000$. Therefore, the MOLFIPP model under fuzzy aspirational goals can be written in light of Eq. (13) as:

$$Maximize\ Z_1 \ = \frac{100Q_1 + 60Q_2 + 35Q_3 + 30Q_4}{2900 - 0.8Q_1 - 0.6Q_2 - 0.7Q_3 - 0.4Q_4} \succsim 25 \tag{40}$$

$$Minimize\ Z_2 \ = \frac{24Q_1 + 24Q_2 + 31.5Q_3 + 14Q_4}{Q_1 + Q_2 + Q_3 + Q_4} \precsim 15 \tag{41}$$

$$Minimize\ Z_3 \ = 4Q_1 + 7Q_2 + 9Q_3 + 4Q_4 \precsim 500 \tag{42}$$

$$Minimize\ Z_4 \ = 565Q_1 + 974Q_2 + 805Q_3 + 1055Q_4 \precsim 80000 \tag{43}$$

Subject to constraint Eqs. (25)–(39). The membership functions for the above model can be computed in light of Eqs. (14) and (15) respectively. Thus for $Z_1 \precsim 25$, i.e.; $L_1 \leqslant Z_1(Q) \leqslant \tilde{g}_1$, Eq. (40) can be transform to:

$$\mu_{Z_1(Q)} \ = \frac{108Q_1 + 166Q_2 + 42Q_3 + 34Q_4 - 29000}{15(2900 - 0.8Q_1 - 0.6Q_2 - 0.7Q_3 - 0.4Q_4)} \tag{44}$$

Similarly, for

$$Z_2 \precsim 15 (i.e., L_1 \leqslant Z_2(Q) \leqslant \tilde{g}_2), Z_3 \precsim 500 (i.e., L_3 \leqslant Z_3(Q) \leqslant \tilde{g}_3), and Z_4 \precsim 80000 (i.e., L_4 \leqslant Z_4(Q) \leqslant \tilde{g}_4)$$

, the respective mermerships are:

$$\mu_{Z_2(Q)} = \frac{6Q_1 + 6Q_2 - 1.5Q_3 + 16Q_4}{15(Q_1 + Q_2 + Q_3 + Q_4)} \tag{45}$$

$$\mu_{Z_3(Q)} = \frac{2600 - 4Q_1 - 7Q_2 - 9Q_3 - 4Q_4}{2100} \tag{46}$$

$$\mu_{Z_4(Q)} \ = \frac{370000 - 565Q_1 - 974Q_2 - 805Q_3 - 1055Q_4}{290000} \tag{47}$$

Standardizing the membership functions to realize the highest degree of aspirational level achievement for the DM goals, Eqs. (44)–(47) can be expressed in terms of Eq. (17) as follows:

$$\frac{108Q_1 + 166Q_2 + 42Q_3 + 34Q_4 - 29000}{15(2900 - 0.8Q_1 - 0.6Q_2 - 0.7Q_3 - 0.4Q_4)} + \delta_1^- - \delta_1^+ = 1, \tag{48}$$

$$\frac{6Q_1 + 6Q_2 - 1.5Q_3 + 16Q_4}{15(Q_1 + Q_2 + Q_3 + Q_4)} + \delta_2^- - \delta_2^+ = 1, \tag{49}$$

$$\frac{2600 - 4Q_1 - 7Q_2 - 9Q_3 - 4Q_4}{2100} + \delta_3^- - \delta_3^+ = 1, \tag{50}$$

$$\frac{370000 - 565Q_1 - 974Q_2 - 805Q_3 - 1055Q_4}{290000} + \delta_4^- - \delta_4^+ = 1, \tag{51}$$

$$where,\ \delta_i^-, \delta_i^+ \geqslant 0,\ \delta_i^- \leqslant 1,\ and\ \delta_i^- \cdot \delta_i^+ = 0,\ \forall i = 1,2,3,4. \tag{52}$$

The following expressions implies from Eqs. (48)–(51) as

$$120Q_1 + 175Q_2 + 52.5Q_3 + 40Q_4 + D_1^- - D_1^+ = 72500, \tag{53}$$

$$-9Q_1 - 9Q_2 - 16.5Q_3 - Q_4 + D_2^- - D_2^+ = 0, \tag{54}$$

$$-4Q_1 - 7Q_2 - 9Q_3 - 4Q_4 + D_3^- - D_3^+ = -500, \tag{55}$$

$$-565Q_1 - 974Q_2 - 805Q_3 - 1055Q_4 + D_4^- - D_4^+ = -80000, \tag{56}$$

where,

$$D_1^- = 15\delta_1^-(2900 - 0.8Q_1 - 0.6Q_2 - 0.7Q_3 - 0.4Q_4), \tag{57}$$

$$D_1^+ = 15\delta_1^+(2900 - 0.8Q_1 - 0.6Q_2 - 0.7Q_3 - 0.4Q_4), \tag{58}$$

$$D_2^- = 15\delta_2^-(Q_1 + Q_2 + Q_3 + Q_4), \tag{59}$$

$$D_2^+ = 15\delta_2^+(Q_1 + Q_2 + Q_3 + Q_4), \tag{60}$$

$$D_3^- = 2100\delta_3^-, \tag{61}$$

$$D_3^+ = 2100\delta_3^+, \tag{62}$$

$$D_4^- = 290000\delta_4^-, \tag{63}$$

$$D_4^+ = 290000\delta_4^+, \tag{64}$$

The D_i^-s can be express in terms of the restriction on δ_i^- in light of Eq. (52) as follows:

$$D_1^- + 12Q_1 + 9Q_2 + 10.5Q_3 + 6Q_4 \leqslant 43500, \tag{65}$$

$$D_2^- - 15Q_1 - 15Q_2 - 15Q_3 - 15Q_4 \leqslant 0, \tag{66}$$

$$D_3^- \leqslant 2100, \tag{67}$$

$$D_4^- \leqslant 290000, \tag{68}$$

The overall goal of this computations is minimizing the total under-achievement of the DM's aspirations. Hence, the complete form of the model can be written in light of Eq. (23) as given below:

$$Min\ Z = \frac{1}{15}\left(D_1^- + D_2^-\right) + \frac{1}{2100}\left(D_3^-\right) + \frac{1}{290000}\left(D_4^-\right)$$

$$\text{Subject to}: \begin{cases} 120Q_1 + 175Q_2 + 52.5Q_3 + 40Q_4 + D_1^- - D_1^+ = 72500, \\ -9Q_1 - 9Q_2 - 16.5Q_3 - Q_4 + D_2^- - D_2^+ = 0, \\ -4Q_1 - 7Q_2 - 9Q_3 - 4Q_4 + D_3^- - D_3^+ = -500, \\ -565Q_1 - 974Q_2 - 805Q_3 - 1055Q_4 + D_4^- - D_4^+ = -80000, \\ 3125Q_1 + 3650Q_2 + 2200Q_3 + 3900Q_4 \leqslant 4500000 \\ 3.2Q_1 + 3.6Q_2 + 2.8Q_3 + 1.2Q_4 \leqslant 15000 \\ 4Q_1 + 7Q_2 + 9Q_3 + 4Q_4 \leqslant 5150 \\ 6Q_1 + 4.5Q_2 + 9Q_3 + 6Q_4 \leqslant 5000 \\ 90Q_1 + 50Q_2 + 55Q_3 + 75Q_4 \leqslant 47000 \\ 565Q_1 + 974Q_2 + 805Q_3 + 1055Q_4 \leqslant 360000 \\ 12500 - 1280Q_1 <= 0; \\ 25000 - 1050Q_2 <= 0; \\ 18750 - 875Q_3 <= 0; \\ 16250 - 460Q_4 <= 0; \\ Q_i \geqslant 0,\ D_i^-, D_i^+ \geqslant 0;\ \forall i = 1,2,3,4. \end{cases} \tag{69}$$

5.2. Sensitivity analysis

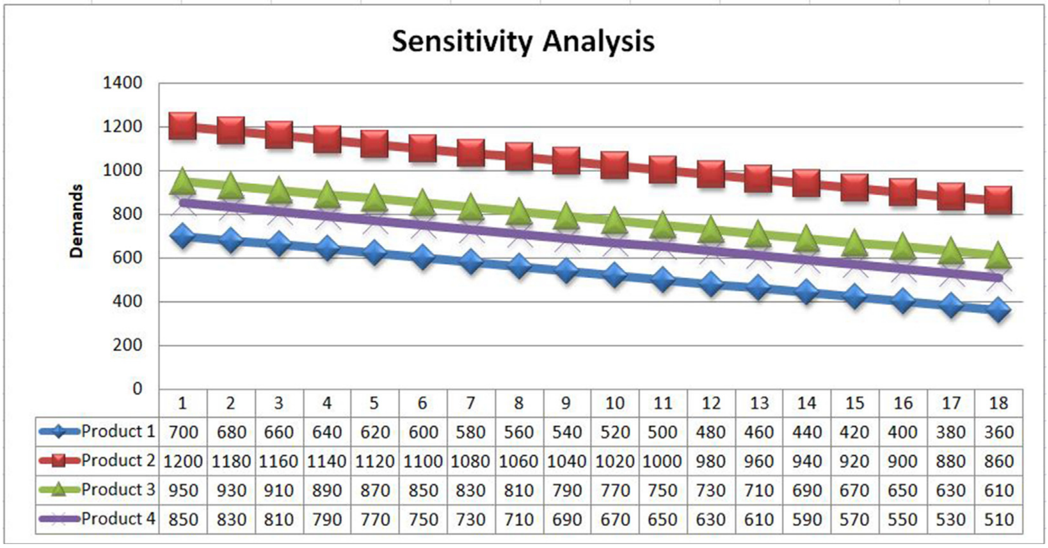
In this section, we analyze the impact of different demand fluctuations on the objective function using sensitivity analysis; this is to enable us to comprehend the effectiveness of the quantity demanded on the optimal value of the objective functions as well as the validity ranges of the solution. Fourty different quantities of demands were considered and analyzed. Since the first objective Z_1, is related to profit which the decision-maker sought to maximize and it depends on the demand quantity as well as the back-ordered quantity, we observed that the values are sensitive to changes in demand. Hence, the objective function values kept changing throughout the different cases considered. While the other three objectives (Z_2, Z_3, *and* Z_4) related to minimization of different entities were constant throughout the analysis, as shown in Table 5. This is because those objectives are independent of the quantity demanded in the inventory and production process, as such any change in the demand will have no direct effects on the goals. A graphical presentation of the analysis is given in Fig. 8. Also, the degrees of achieving the aspirational goals of the DM (μ_i) are computed in the analysis.

6. Result analysis and discussion

Managing the ever-increasing emissions and maintaining and conserving the environment becomes very imperative to the top decision-makers in the SCM of the inventory and production industries. The sustainable green supply chain is crucial. Moreover, not only to the business entities in the inventory and production management but also, to the customers, government and international organizations as the emissions in the production and inventory contributes immensely to the global warming which affects the economy globally, hence, the need to mitigate the process. This study investigated the various cost of carbon dioxide emissions associated with holding inventory in the production of four items in the supply chain management as well as optimizing the resulting profit and incurred costs. Four models were proposed which simultaneously optimize the profit while minimizing the back-ordered quantity and various emission cost in an attempt to preserve the eco-friendly environment. The model is formulated as a multi-item inventory fractional programming problem and coded into LINGO optimization package version 16.0. The

Table 5 Sensitivity analysis for different values of demand.

S. No.	(D_1, D_2, D_3, D_4)	Q_1	Q_2	Q_3	Q_4	Z_1	Z_2	Z_3	Z_4	μ_1	μ_2	μ_3	μ_4
1	(1120,1620,1380,1280)					Infeasible	Solution	found					
2	(1100,1600,1350,1250)	450.6893	52.1987	21.4286	35.3261	10.1912	23.656	2502.309	360000	0.0127	0.4229	0.0465	0.0345
	↑↑↑↑					↑				↑			
3	(700,1200,950,850)	450.6893	52.1987	21.4286	35.3261	15.122	23.656	2502.309	360000	0.3415	0.4229	0.0465	0.0345
4	(680,1180,930,830)	450.6893	52.1987	21.4286	35.3261	15.496	23.656	2502.309	360000	0.3664	0.4229	0.0465	0.0345
5	(660,1160,910,810)	450.6893	52.1987	21.4286	35.3261	15.890	23.656	2502.309	360000	0.3927	0.4229	0.0465	0.0345
6	(640,1140,890,790)	450.6893	52.1987	21.4286	35.3261	16.305	23.656	2502.309	360000	0.4203	0.4229	0.0465	0.0345
7	(620,1120,870,770)	450.6893	52.1987	21.4286	35.3261	16.741	23.656	2502.309	360000	0.4494	0.4229	0.0465	0.0345
8	(600,1100,850,750)	450.6893	52.1987	21.4286	35.3261	17.202	23.656	2502.309	360000	0.4801	0.4229	0.0465	0.0345
9	(580,1080,830,730)	450.6893	52.1987	21.4286	35.3261	17.689	23.656	2502.309	360000	0.5126	0.4229	0.0465	0.0345
10	(560,1060,810,710)	450.6893	52.1987	21.4286	35.3261	18.204	23.656	2502.309	360000	0.5469	0.4229	0.0465	0.0345
11	(540,1040,790,690)	450.6893	52.1987	21.4286	35.3261	18.750	23.656	2502.309	360000	0.5833	0.4229	0.0465	0.0345
12	(520,1020,770,670)	450.6893	52.1987	21.4286	35.3261	19.330	23.656	2502.309	360000	0.6220	0.4229	0.0465	0.0345
13	(500,1000,750,650)	450.6893	52.1987	21.4286	35.3261	19.946	23.656	2502.309	360000	0.6631	0.4229	0.0465	0.0345
14	(480,980,730,630)	450.6893	52.1987	21.4286	35.3261	20.604	23.656	2502.309	360000	0.7069	0.4229	0.0465	0.0345
15	(460,940,710,610)	450.6893	52.1987	21.4286	35.3261	21.306	23.656	2502.309	360000	0.7537	0.4229	0.0465	0.0345
16	(440,920,690,590)	450.6893	52.1987	21.4286	35.3261	22.058	23.656	2502.309	360000	0.8039	0.4229	0.0465	0.0345
17	(420,900,670,570)	450.6893	52.1987	21.4286	35.3261	22.865	23.656	2502.309	360000	0.8577	0.4229	0.0465	0.0345
18	(400,880,650,550)	450.6893	52.1987	21.4286	35.3261	23.733	23.656	2502.309	360000	0.9155	0.4229	0.0465	0.0345
19	(380,860,630,530)	450.6893	52.1987	21.4286	35.3261	24.669	23.656	2502.309	360000	0.9779	0.4229	0.0465	0.0345
20	(360,840,610,510)					Infeasible	Solution	found					



	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Product 1	700	680	660	640	620	600	580	560	540	520	500	480	460	440	420	400	380	360
Product 2	1200	1180	1160	1140	1120	1100	1080	1060	1040	1020	1000	980	960	940	920	900	880	860
Product 3	950	930	910	890	870	850	830	810	790	770	750	730	710	690	670	650	630	610
Product 4	850	830	810	790	770	750	730	710	690	670	650	630	610	590	570	550	530	510

Fig. 8 Graphical representation of sensitivity analysis for different demands.

compromised solutions are obtained as can be seen in Table 4. Sensitivity analysis with varying demands has been carried out considering forty different cases, in order to understand the effects of the changes on the optimal solution. The optimal order quantities are determined, and the range of its feasibility obtained. It has been found from the sensitivity analysis that, even if the demands for the four items increases up to (1100,1600,1350,1250) and decreases down to (380,860,630,530) respectively, the actual result is valid. The maximum degrees of achievement corresponding to various demand for the different fuzzy aspirational goals are found to be 0.9779, 0.4229,0.0465 and 0.0345 for objective 1, 2, 3, and 4 respectively as can be seen in Table 5.

6.1. Managerial insights and practical implications

The integration of environmentally challenging issue into the model formulation serves as a tool in helping operational managers to realize the usefulness of this study, where a DM always wish to simultaneously optimize various cost and profit related to the management of production and sustainable inventory in manufacturing industries directly. The model considered various input parameters such as holding and ordering costs per item per year, purchasing and selling prices, cost related to green investments such as CO_2 emission, pollution control cost, environmental waste disposal cost as well as electricity consumption cost during the production run. The aspirational goal of DM is considered as fuzzy to enable the operational managers to have some flexibility within which it operates as demand fluctuates due to uncertainty inherently in the process. Green supply chain collaborating with environmental issues is a significant component of GSC inventory and production management. Specifically, the research focus to determine the complexity in predicting optimal required quantity to simultaneously minimize the cost of GSC inventory and production management system. The possibility of demand backorder and its inherent uncertainty are considered and incorporated in the proposed model, unlike the traditional norms that does not include the return of items. The real-world practices reflect this our approach in many sectors of the economy involving complex chain of raw material and consumer intensity, such as electronic industries, aerospace and automobile among others. The proposed model captured the uncertainty effects on periodic customer demand, raw material costs, environmental emissions costs due to transportation, and availability of goods and materials return by customer due to defectiveness. The advantage of the proposed work is that, the worse cases (costs) can be easily minimize by the DMs and maximize the better once (profit). The wide consideration of uncertain parameters in our model, and implementing it with numerical data, makes it effective and called for decision-makers in manufacturing and inventory related industries to implement the findings and approach in handling the environmental safety while in business. The sensitivity analysis reveals to the DM a range of values within which his solution is valid. In other words, the top management of the firm are well-informed about the future fluctuations in demands from their existing as well as prospective customers; this could enable them to plan and diversify their strength in order to remain productive in the business.

6.2. Research findings and limitaions

This study contributes to the bank of knowledge by way of proposing a mathematical multi-objective multi-item model of a sustainable green supply chain for inventory and production management. The propose work minimize the total expected cost of GHGs emissions, environmental cost of waste disposal, production and inventory holding cost and optimizes the profit to the ratio of backorder quantity. It has also considered different objectives related to the waste produced by the inventory system per cycle and the total penalty cost incurred in the system. Additionally, deterioration in the total ordering quantity is considered. However, the major limitation is that a fixed price, and no quantity discount are considered.

7. Conclusion and future work

This paper considered a green investment in inventory and production management. The paper proposes a multi-objective multi-item fractional inventory model to maximize the profit with total back-ordered quantity simultaneously, optimize the cost related to inventory holding cost, various carbon-dioxide emission cost, and minimize possible pollution during the inventory production management. The proposed model is formulated using the concept of fuzzy goal programming and numerically illustrated with a case study and solve with a LINGO optimization software. The model gives an efficient and promising ideal solution with overall achievement values that encompasses the decision-makers satisfaction having multiple goals and also fluctuating demand has been taken care of by the fuzzy aspirational goals. Therefore, an effective and optimal trade-off between the economic gains (profit) and its environmental responsibilities (green technology) is established by simultaneously maximizing profit and minimizing the costs of carbon emissions, environmental pollutions, electricity consumptions during production, and emissions due to transportation of finished products. However, an approach with uncertainty varies in the literature and scope of the inventory studies. For instance, determination of demand with price break, quantity discount could be investigated in future by interested researchers using probabilistic methods, other fuzzy techniques or simulation study. Furthermore, this model can be extended to include continuous price and or price break in the items. Besides, late delivery and shortages of items can be considered as an extension of the proposed model. Also, deteriorating items with expiration duration could be possibly considered as an extension to this work.

CRediT authorship contribution statement

Ahmad A. H. Ahmadini: Designed, Conceptualization, Publication support. **Umar Muhammad Modibbo:** Designed, Conceptualization, Writing - original draft, Formal analysis. **Irfan Ali:** Designed, Conceptualization, Supervision. **Ali Akbar Shaikh:** Designed, Conceptualization.

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