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*Research Article*

# Modelling Sustainable Development Aspects within Inventory Supply Strategies

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Nowadays, inventory management is a tool that must be extended to cover all aspects of the supply chain (SC). One of these aspects is Sustainable Development (SD) which emphasizes the balance between economic well-being, natural resources, and society. As inventory involves the use of natural and economic resources, the integration of SD criteria is important for a more efficient and sustainable SC. In this work, the most important SD variables associated with inventory management were identified. These variables were integrated as cost elements within a nondeterministic inventory control model to include SD criteria within inventory supply strategies. Through the assessment of the proposed integrated model, it was determined that, although SD practices involve additional investments, specific practices such as reuse/recycling and government incentives can increase revenue and profits. This is important for the development of government and business strategies to perform sustainable practices.

## 1. Introduction

Sustainable Development (SD) has its beginnings in the 1980s when the United Nations (UN) requested an investigation about natural resources and their situation in the world in the face of the evident deterioration of the environment and natural resources. This investigation led to the report entitled "Our Common Future" [1] where the term "Sustainable Development" was defined for the first time [2]. SD integrates the concern of the resource capacity of natural systems with the social, political, and economic challenges of humanity [3].

The UN and the OECD (Organization for Economic Cooperation and Development) have been working with member countries to make appropriate recommendations to reduce the impact of inefficient economic practices on the sustainable aspects of the environment and society. Within this context, the manufacture and service industries are two of the main sectors whose practices impact on the economic, environmental, and social aspects.

If unattended, the impacts on these aspects are expected to worsen as more people would require products and services, compromising the availability of environmental resources for production of raw materials. Thus, finding new solutions to achieve sustainable consumption and production is of main interest for companies (however, this requires an understanding of the environmental and social effects of products and services).

The distribution of materials and products throughout the SC is one of the major contributors to emissions of greenhouse compounds with high logistics costs [4]. Within this context, inventory management is the component of the SC which involves operations that impact on economic, environmental, and social aspects as it involves production and distribution operations that generate significant pollution (e.g., $CO_2$ emissions and product waste) and economic loss due to inefficient management practices [5–7].

Hence, the importance of this work consists of the development of an inventory model to integrate SD criteria within the SC to reduce economic loss and negative impacts on SD.

Table 1: Review of works on inventory control with sustainable aspects (own work).

| Work | Description | Variable associated to sustainability |
|---|---|---|
| [5] | EOQ model with the vehicle's cost of $CO_2$ emissions | Economic lot size<br>$CO_2$ emissions |
| [9] | EOQ model with the cost of $CO_2$ emissions associated to logistics and warehousing operations | Economic lot size<br>Water footprint<br>$CO_2$ emissions<br>Cap-and-trade incentives |
| [10] | Multiobjective EOQ model with the cost of $CO_2$ emissions | Economic lot size<br>Water footprint<br>$CO_2$ emissions<br>Environmental and social criteria |
| [11] | EOQ model with facility location that integrates $CO_2$ restrictions on multiple business units | Economic lot size<br>$CO_2$ emissions and taxes<br>Cap-and-trade incentives |
| [12] | EOQ and EPQ models with green costs associated to warehousing and production | Economic lot size<br>$CO_2$ emissions and taxes<br>Cap-and-trade incentives |
| [13] | EOQ model with carbon footprint and transportation costs | Economic lot size<br>$CO_2$ emissions |
| [14] | EOQ model with sustainability considerations | Economic lot size<br>$CO_2$ emissions<br>Carbon tax<br>Carbon offsets and social criteria |

For the development of the model, the multicriteria analysis was performed to identify the most significant factors of the environmental, economic, and social aspects that impact on the SD of inventory supply management.

The advances of this work are presented as follows: in Section 2, a review on SD and sustainable inventory models is presented; then, in Section 3, the analysis to determine the SD factors associated to inventory is described. Section 4 presents the development of the integrated inventory control model with the cost variables representing these SD factors. A test instance developed to assess the outcomes of the inventory model is presented in Section 5 with a discussion regarding its results. Finally, Section 6 presents our conclusions and future work.

## 2. Sustainable Inventory Models

As discussed in [8], the formulation of sustainable tools for SC requires a multidisciplinary approach. Thus, the development of an inventory model with SD criteria involves multidisciplinary complexity [2] with different policies or strategies to reduce contaminants and economic loss [6]. In this review, deterministic and nondeterministic inventory models that have addressed sustainable aspects were analyzed. Table 1 presents a detailed analysis regarding the most recent models which have included some sustainable variables within their formulations.

Bonney and Jaber [5] addressed the importance of analyzing the relation of inventory to the environment and whether if it is possible to create environmentally responsible inventory planning systems. Their results suggested that ordering items in larger quantities (less frequent orders) in contrast to the traditional economic order quantity (EOQ) model can lead to reducing transportation costs and consequent $CO_2$ emissions. Furthermore, their results implied that a cost-benefit analysis can be performed by a joint cost function between the company's benefits and the inventory costs.

Hua et al. [9] addressed the trade in carbon emissions as an effective mechanism to reduce them. This was proposed by investigating how companies manage carbon footprints in inventory management under the carbon emission trading mechanism. They derived the optimal order quantity and analytically and numerically examined the impacts of carbon trade, carbon price, and carbon cap on order decisions, carbon emissions, and total cost.

Bouchery et al. [10] developed a sustainable EOQ model. Their results were used to provide some insights about the effectiveness of different regulatory policies to control carbon emissions. They also used an interactive procedure which allowed the decision-maker to quickly identify the best option among these solutions. The proposed interactive procedure led to a new combination of multicriteria decision analysis techniques.

Benjaafar et al. [11] used the EOQ and News Vendor models to study the extent to which carbon reduction

Table 2: Supply chain metrics: performance indicators on sustainability [16].

| Social | Economic | Environmental |
|---|---|---|
| *Health and safety*<br>(1) Number of accidents (employees)<br>(2) Work conditions<br>(3) Number of accidents (nonemployees) | *Quality*<br>(1) On-time delivery<br>(2) Customer satisfaction<br>(3) Order fill rate<br>(4) Product/service availability | *Emissions*<br>(1) Level of $CO_2$ emissions<br>(2) Level of $CO_2$ emission from transport processes<br>(3) Level of $CO_2$ emission from infrastructure |
| *Noise*<br>(1) Noise volume<br>(2) Time of noise emission<br>(3) Noise emission in urban areas | *Efficiency*<br>(1) Distribution costs<br>(2) Total costs<br>(3) Transport costs<br>(4) Loading capacity utilization | *Natural resources utilization*<br>(1) Energy use<br>(2) Water consumption<br>(3) Energy consumption/revenue |
| *Employees*<br>(1) Employee skills<br>(2) Employee satisfaction<br>(3) Percent of labor cost spent on training | *Responsiveness*<br>(1) Stock-outs<br>(2) Product lateness<br>(3) Lead time<br>(4) Forecast accuracy | *Waste and recycling*<br>(1) Level of waste<br>(2) Level of products recycled<br>(3) Level of products reused |

requirements can be addressed by operational adjustments, as an alternative (or a supplement) to costly investments in carbon-reducing technologies. They also used these models to (a) investigate the impact of collaboration among companies within the same SC on their costs and carbon emissions and (b) to study the incentives that companies might have in seeking such cooperation.

Tao et al. [12] researched the joint optimal decisions on lot size in a coordinated SC between a retailer and a manufacturer under the carbon tax and cap-and-trade mechanisms. The comprehensive cost-based models were proposed to capture the influence of two carbon regulatory schemes on business decisions in a coordinated two-stage SC.

Battini et al. [13] linked sustainability aspects to the raw material lot size, from the beginning of the order purchase to its delivery at the buyer's plant. Thus, the environmental impact of transportation and inventory was incorporated into the EOQ model. The approach was applied to represent data from industrial problems to assess the impact of sustainability considerations on purchasing decisions when compared to traditional approaches.

Arslan and Turkay [14] discussed on sustainable aspects for the standard EOQ model with a single item at a single location with no backlogging, constant lead times, and an unlimited supply. Also, they discussed on relaxations to consider multiple items at multiple locations with planned backorders, variable lead times, finite production rates, quantity discounts, imperfect quality, and resource constraints such as warehouse space.

As discussed, while companies have made efforts to increase profits by looking for the economic factor, research has provided insights regarding the importance of the environmental and social factors for this goal, and currency markets are moving in that direction [2, 15]. The works reviewed in Table 1 have demonstrated that the integration of these factors within the inventory control techniques can improve on achieving sustainability without conflicting with the economic aspect of inventory management.

In this context, the proposed research contributes with an integrated inventory supply model to address a more comprehensive integration of the economic, environmental and social factors. In contrast to the works reviewed in Table 1, where up to three variables were analyzed, the present work analyzes six variables associated with SD factors. These were identified and modelled as cost elements for their integration within an inventory control technique for uncertain demand, which is a common feature in nowadays markets. The advances of this model are described in the following sections.

## 3. Determination of Variables Associated to SD Factors in Inventory Management

The determination of variables associated with the SD factors can be considered a multicriteria task. This is because each factor is integrated by diverse decisions, costs, and resources that affect the sustainability of the SC. Also, depending on the context, qualitative and quantitative assessment of the importance of each factor may lead to different conclusions. In the example, in [16] it was mentioned that economic factors should be the dominant ones in inventory management. On the other hand, in [14] it was considered that environmental and social factors should be considered due to the current environmental situation.

For the present work, we extended the analyses reported in [16, 17] on metrics to measure SC performance and evaluation of sustainable supply chain indicators. The work reported in [16] concluded that the most important SC metrics related to sustainability were those presented in Table 2.

To provide a more general model, we performed a focus group discussion with different professionals in the manufacturing and logistics fields for the assessment of these metrics on inventory management. In this way, the metrics presented in Table 2 were extended to those presented in Table 3.

With this information, we proceeded to determine the most important variables or metrics between each other based on a multicriteria analysis. For the selection of the analysis tool, we studied the work reported in [17] where the AHP technique led to determine that environmental

Table 3: Supply chain metrics: performance indicators on sustainability (own work).

| Social | Economic | Environmental |
|---|---|---|
| *Health and safety*<br>(1) Number of accidents (employees)<br>(2) Number of accidents (nonemployees)<br>(3) Number of accidents associated to company's vehicles<br>(4) Wireless electronics conditions<br>(5) Toxic and hazardous emissions | *Quality*<br>(1) On-time delivery<br>(2) Customer satisfaction<br>(3) Order fill rate<br>(4) Product quality<br>(5) Supplier performance | *Emissions*<br>(1) Level of $CO_2$ emissions<br>(2) Level of $CO_2$ emission from transport processes<br>(3) Level of $CO_2$ emission from infrastructure<br>(4) Carbon footprint—ordering<br>(5) Carbon footprint—holding |
| *Waste*<br>(1) Water pollution<br>(2) Air pollution<br>(3) Solid waste | *Efficiency*<br>(1) Information management costs<br>(2) Distribution costs<br>(3) Inventory costs<br>(4) Transport costs<br>(5) Loading capacity utilization | *Natural resources utilization*<br>(1) Energy use<br>(2) Water consumption<br>(3) Energy consumption/revenue<br>(4) Fossil fuel consumption<br>(5) Energy efficiency per ton kilometer |
| *Employees*<br>(1) Hours efficiently worked (energy optimization)<br>(2) Clean workplace<br>(3) Good use of work tools<br>(4) Classification of waste in work areas<br>(5) Disposal of work waste | *Responsiveness*<br>(1) Stock-outs<br>(2) Lead time<br>(3) Forecast accuracy<br>(4) New product—time to market<br>(5) New product—time to first date | *Waste and recycling*<br>(1) Level of waste<br>(2) Level of products recycled<br>(3) Level of products reused<br>(4) Level of landfill waste<br>(5) Level of biodegradable materials used |

and social factors could contribute more to the sustainability of the Indian automotive industry.

*3.1. AHP Analysis.* For our analysis, the goal of the AHP is defined as the identification of the most important alternatives to be modelled as cost variables within the proposed inventory model. For this, the SD factors are set as the criteria at level 1 of the AHP structure. Then, the aspects of each factor are considered as the subcriteria for level 2. Finally, the alternatives from which the variables will be identified and modelled are set at level 3 of the AHP structure. Figure 1 presents the description of the AHP model with the associated abbreviations.

Figure 2 presents the weights (i.e., importance) estimated for the criteria, subcriteria and alternatives defined by the AHP structure of Figure 1. These weights were estimated based on the feedback of professionals in the manufacturing and logistics fields and the results reported in [16]. The details of the professionals' profiles are presented in Table 4.

With this data, the AHP weights associated with the interactions between all criteria, subcriteria, and alternatives were computed. These are presented in Table 5.

From Table 5 it is obtained that the economic criterion (*Eco*) is the most significant with weight = 0.5936. The environment criterion (*Env*) is the second most significant with weight = 0.2493, and the social criterion (*Soc*) is the least significant with weight = 0.1571. For each criterion, also the most significant subcriterion is determined. For example, for *Eco*, the subcriterion responsiveness (*Eco_R*) is the most significant with weight = 0.2815. Finally, for each subcriterion, the most significant alternative is obtained (marked in bold). By following the previous example, for *Eco_R*, the most significant alternative is lead time (*A_Eco_R3*) with weight = 0.1114 (see abbreviations presented in Figure 1).

Table 6 presents the interpretation of the results of the AHP analysis of Table 5. Note that these results will support the definition of variables that will be modelled as cost elements for the proposed inventory control model with SD criteria.

As presented, there are nine variables (alternatives) associated with the sustainability of inventories through all SD factors (criteria). To equally address the variables through the SD factors, the two most significant variables were selected from each criterion. These are summarized in Table 7.

## 4. Development of the SD Inventory Model

Figure 3 presents the general structure of the SC which consists of three main entities: raw material suppliers, end-product manufacturers, and end-product retailers or clients. Here, the final entities determine the global requirements (demand) of end-products to be produced and transported through the SC. These requirements are to be periodically covered by the delivery of lots of size $Q$ which is the basis of the economic aspect of inventory control management. As presented, the availability of $Q$ depends of different aspects of the SC which are related to the SD variables identified in Table 7.

Thus, the integration of each SD variable within the inventory model considering the relationships and dependencies identified in Figure 3 is performed as follows:

(i) Quality involves producing products with the minimum defects and the features required by the customer. Within SD criteria, achieving the highest quality supports the reduction of unnecessary waste and reconditioning processes. As the rejection of a lot is based on the individual detection of defects, the quality cost $C_Q$ is considered as an investment to be associated with units

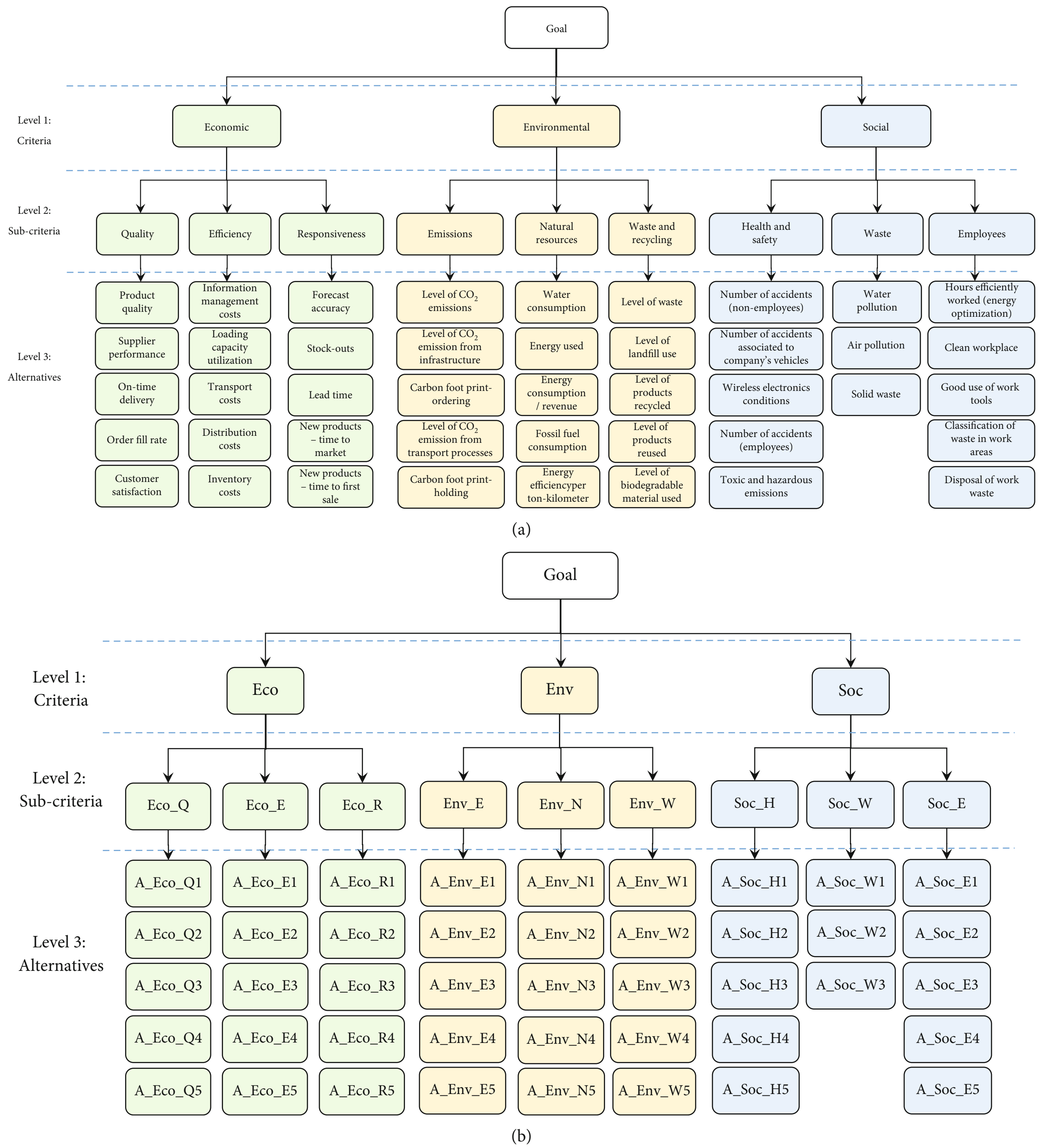


FIGURE 1: Hierarchical structure of the information reported in Table 3: (a) descriptive structure and (b) abbreviated structure (own work).

(ii) Lead time is associated to prompt delivery of products or raw material. Inefficient delivery is associated with rejection rates of lots, unnecessary additional transportation costs, and $CO_2$ emissions. In this regard, failure to comply with the lead time can be considered as a penalty cost $C_{LT}$ to be associated to lots

(iii) $CO_2$ emissions are associated with transportation. If lot sizes are not adequately estimated, unnecessary additional transportation may take place which would produce $CO_2$ emissions. Thus, the emission cost $C_E$ is considered as a cost associated with the transportation of lots

(iv) The level of products that are reused is an important sustainability aspect. This practice consists of using an item for other purposes, either similarly to the original purpose or to different ones. This is different from recycling because it does not involve reconditioning or breaking down into raw materials. Thus, it can lead to save time, money, energy, and other resources within the company [18, 19]. Depending

Consistency: 0.0516; Weightiness to "goal": 1.0000; $\lambda_{max}$: 3.0536

| Goal | Eco | Soc | Env | $W_i$ |
|---|---|---|---|---|
| Eco | 1.00 | 3.00 | 3.00 | 0.59 |
| Soc | 0.33 | 1.00 | 0.50 | 0.16 |
| Env | 0.33 | 2.00 | 1.00 | 0.25 |

Consistency: 0.0516; Weightiness to "goal": 0.5936; $\lambda_{max}$: 3.0536

| Eco | Eco_Q | Eco_E | Eco_R | $W_i$ |
|---|---|---|---|---|
| Eco_Q | 1.00 | 2.00 | 1.00 | 0.38 |
| Eco_E | 0.50 | 1.00 | 0.25 | 0.15 |
| Eco_R | 1.00 | 4.00 | 1.00 | 0.47 |

Consistency: 0.0537; Weightiness to "goal": 0.2234; $\lambda_{max}$: 5.2406

| Eco_Q | A_Eco_Q1 | A_Eco_Q2 | A_Eco_Q3 | A_Eco_Q4 | A_Eco_Q5 | $W_i$ |
|---|---|---|---|---|---|---|
| A_Eco_Q1 | 1.00 | 0.14 | 0.17 | 0.20 | 0.11 | 0.03 |
| A_Eco_Q2 | 7.00 | 1.00 | 0.50 | 0.33 | 0.25 | 0.12 |
| A_Eco_Q3 | 6.00 | 2.00 | 1.00 | 0.50 | 0.33 | 0.17 |
| A_Eco_Q4 | 5.00 | 3.00 | 2.00 | 1.00 | 0.50 | 0.25 |
| A_Eco_Q5 | 9.00 | 4.00 | 3.00 | 2.00 | 1.00 | 0.42 |

Consistency: 0.0787; Weightiness to "goal": 0.0887; $\lambda_{max}$: 5.3524

| Eco_E | A_Eco_E1 | A_Eco_E2 | A_Eco_E3 | A_Eco_E4 | A_Eco_E5 | $W_i$ |
|---|---|---|---|---|---|---|
| A_Eco_E1 | 1.00 | 0.33 | 0.13 | 0.14 | 0.11 | 0.03 |
| A_Eco_E2 | 3.00 | 1.00 | 0.20 | 0.14 | 0.13 | 0.05 |
| A_Eco_E3 | 8.00 | 5.00 | 1.00 | 0.50 | 0.33 | 0.18 |
| A_Eco_E4 | 7.00 | 7.00 | 2.00 | 1.00 | 0.25 | 0.24 |
| A_Eco_E5 | 9.00 | 8.00 | 3.00 | 4.00 | 1.00 | 0.50 |

Consistency: 0.0853; Weightiness to "goal": 0.2815; $\lambda_{max}$: 5.3821

| Eco_R | A_Eco_R1 | A_Eco_R2 | A_Eco_R3 | A_Eco_R4 | A_Eco_R5 | $W_i$ |
|---|---|---|---|---|---|---|
| A_Eco_R1 | 1.00 | 0.25 | 0.20 | 2.00 | 4.00 | 0.13 |
| A_Eco_R2 | 4.00 | 1.00 | 0.50 | 5.00 | 4.00 | 0.32 |
| A_Eco_R3 | 5.00 | 2.00 | 1.00 | 3.00 | 4.00 | 0.41 |
| A_Eco_R4 | 0.50 | 0.20 | 0.33 | 1.00 | 2.00 | 0.09 |
| A_Eco_R5 | 0.25 | 0.25 | 0.25 | 0.50 | 1.00 | 0.06 |

Consistency: 0.0176; Weightiness to "goal": 0.2493; $\lambda_{max}$: 3.0183

| Env | Env_E | Env_N | Env_W | $W_i$ |
|---|---|---|---|---|
| Env_E | 1.00 | 1.00 | 0.33 | 0.21 |
| Env_N | 1.00 | 1.00 | 0.50 | 0.24 |
| Env_W | 3.00 | 2.00 | 1.00 | 0.55 |

Consistency: 0.0916; Weightiness to "goal": 0.0523; $\lambda_{max}$: 5.4103

| Env_E | A_Env_E1 | A_Env_E2 | A_Env_E3 | A_Env_E4 | A_Env_E5 | $W_i$ |
|---|---|---|---|---|---|---|
| A_Env_E1 | 1.00 | 0.33 | 0.33 | 0.20 | 0.17 | 0.05 |
| A_Env_E2 | 3.00 | 1.00 | 0.33 | 0.17 | 0.14 | 0.07 |
| A_Env_E3 | 3.00 | 3.00 | 1.00 | 0.33 | 0.25 | 0.12 |
| A_Env_E4 | 5.00 | 6.00 | 3.00 | 1.00 | 0.25 | 0.25 |
| A_Env_E5 | 6.00 | 7.00 | 4.00 | 4.00 | 1.00 | 0.51 |

Consistency: 0.0905; Weightiness to "goal": 0.0599; $\lambda_{max}$: 5.4054

| Env_N | A_Env_N1 | A_Env_N2 | A_Env_N3 | A_Env_N4 | A_Env_N5 | $W_i$ |
|---|---|---|---|---|---|---|
| A_Env_N1 | 1.00 | 0.20 | 0.13 | 0.17 | 1.00 | 0.05 |
| A_Env_N2 | 5.00 | 1.00 | 0.33 | 0.20 | 4.00 | 0.15 |
| A_Env_N3 | 8.00 | 3.00 | 1.00 | 0.33 | 3.00 | 0.26 |
| A_Env_N4 | 6.00 | 5.00 | 3.00 | 1.00 | 5.00 | 0.48 |
| A_Env_N5 | 1.00 | 0.25 | 0.33 | 0.20 | 1.00 | 0.06 |

Consistency: 0.0934; Weightiness to "goal": 0.1371; $\lambda_{max}$: 5.4184

| Env_W | A_Env_W1 | A_Env_W2 | A_Env_W3 | A_Env_W4 | A_Env_W5 | $W_i$ |
|---|---|---|---|---|---|---|
| A_Env_W1 | 1.00 | 2.00 | 0.11 | 0.20 | 0.17 | 0.06 |
| A_Env_W2 | 0.50 | 1.00 | 0.14 | 0.25 | 0.25 | 0.05 |
| A_Env_W3 | 9.00 | 7.00 | 1.00 | 0.50 | 0.50 | 0.26 |
| A_Env_W4 | 5.00 | 4.00 | 2.00 | 1.00 | 0.50 | 0.27 |
| A_Env_W5 | 6.00 | 4.00 | 2.00 | 2.00 | 1.00 | 0.36 |

Consistency: 0.0036; Weightiness to "goal": 0.1571; $\lambda_{max}$: 3.0037

| Soc | Soc_H | Soc_W | Soc_E | $W_i$ |
|---|---|---|---|---|
| Soc_H | 1.00 | 0.33 | 0.20 | 0.11 |
| Soc_W | 3.00 | 1.00 | 0.50 | 0.31 |
| Soc_E | 5.00 | 2.00 | 1.00 | 0.58 |

Consistency: 0.0934; Weightiness to "goal": 0.0172; $\lambda_{max}$: 5.4184

| Soc_H | A_Soc_H1 | A_Soc_H2 | A_Soc_H3 | A_Soc_H4 | A_Soc_H5 | $W_i$ |
|---|---|---|---|---|---|---|
| A_Soc_H1 | 1.00 | 2.00 | 0.11 | 0.20 | 0.17 | 0.06 |
| A_Soc_H2 | 0.50 | 1.00 | 0.14 | 0.25 | 0.25 | 0.05 |
| A_Soc_H3 | 9.00 | 7.00 | 1.00 | 0.50 | 0.50 | 0.26 |
| A_Soc_H4 | 5.00 | 4.00 | 2.00 | 1.00 | 0.50 | 0.27 |
| A_Soc_H5 | 6.00 | 4.00 | 2.00 | 2.00 | 1.00 | 0.36 |

Consistency: 0.0707; Weightiness to "goal": 0.0485; $\lambda_{max}$: 3.0735

| Soc_W | A_Soc_W1 | A_Soc_W2 | A_Soc_W3 | $W_i$ |
|---|---|---|---|---|
| A_Soc_W1 | 1.00 | 3.00 | 4.00 | 0.61 |
| A_Soc_W2 | 0.33 | 1.00 | 3.00 | 0.27 |
| A_Soc_W3 | 0.25 | 0.33 | 1.00 | 0.12 |

Consistency: 0.0956; Weightiness to "goal": 0.0913; $\lambda_{max}$: 5.4283

| Soc_E | A_Soc_E1 | A_Soc_E2 | A_Soc_E3 | A_Soc_E4 | A_Soc_E5 | $W_i$ |
|---|---|---|---|---|---|---|
| A_Soc_E1 | 1.00 | 0.25 | 0.11 | 0.17 | 0.13 | 0.03 |
| A_Soc_E2 | 4.00 | 1.00 | 0.25 | 0.20 | 0.17 | 0.07 |
| A_Soc_E3 | 9.00 | 4.00 | 1.00 | 0.50 | 0.20 | 0.17 |
| A_Soc_E4 | 6.00 | 5.00 | 2.00 | 1.00 | 0.33 | 0.23 |
| A_Soc_E5 | 8.00 | 6.00 | 5.00 | 3.00 | 1.00 | 0.50 |

FIGURE 2: Weights (importance) of criteria, subcriteria and alternatives for the AHP analysis (own work).

TABLE 4: Profiles of eight professionals considered for the AHP analysis: SC: supply chain; IM: inventory management; SD: Sustainable Development (own work).

| Field | $P_1$ | $P_2$ | $P_3$ | $P_4$ | $P_5$ | $P_6$ | $P_7$ | $P_8$ |
|---|---|---|---|---|---|---|---|---|
| SC | X | X | X | X | X | X | X | X |
| IM | X | X | X | X | X | X | X | X |
| SD | X | X | | X | | | | X |

of the effort or additional steps for reuse (i.e., change of packaging/labelling and washing), this can include a small cost with an important return value. In this case, it is considered as an incentive $C_{PR}$ which is dependent of a percentage of a lot

(v) Water pollution is an aspect which is commonly omitted in the practice, and it can take place in any stage of the production process (i.e., cleaning and maintenance). The water pollution cost $C_{WP}$ is considered as a shared-cost associated with producing a unit of product

(vi) Disposal of work waste is also an aspect that is not considered in practice. This requires additional investment for green practices associated with proper disposal of units which, if the quality is not absolute, is dependent on a percentage of the lot size. Thus, $C_{DW}$ is considered as a cost associated with the lot size

In inventory management tools, there are three main costs: holding costs, ordering costs, and safety stock costs [20]. An inventory control policy must determine a balance between these costs to reduce the impact on the SC.

One of the most widely used models for inventory control under uncertainty is the continuous review model or $(Q, R)$ model [21], where $Q$ defines the optimal lot size and $R$ the reorder point which depends on the lead time and average demand [22].

In general terms, the $(Q, R)$ model considers the following constants and variables: $C_o$ is the order cost per lot; $C_h$ is the holding cost per unit of product; $C$ is the purchase cost per unit of product; $p$ is the stock-out cost per unit of product; $D$ is the cumulative demand for a planning horizon, and $d$ is the average daily, weekly, or monthly demand; LT is the lead time; $\mu_{LT}$ and $\sigma_{LT}$ are the mean and standard deviation of the demand during the lead time; $L(z)$ is the standard loss function; $K$ is the expected shortage of units of products per cycle. The economic lot quantity $Q$ and the reorder point $R$ then are estimated as presented in Figure 4 [23].

Within the determination of the lot size, $pK$ is equivalent to $C_{LT}$ as it is associated with the units of products not delivered per inventory cycle. Another cost to be performed each time a lot is ordered is the transportation cost. While this can be considered within $C_o$, the $CO_2$ emission costs are not frequently considered. In [23], a cost metric, based on the transportation distance and $CO_2$ emissions generated per kilometer, was determined as follows:

$$C_E = E_{CO_2} \times \text{dist} \times t_{CO_2}, \tag{1}$$

where $E_{CO_2}$ is the average $CO_2$ emission per kilometer in grams, dist is the total traveled distance between the supplier and the warehouse, and $t_{CO_2}$ is a $CO_2$ emission tax per gram.

About costs associated with units of products, the quality cost $C_Q$ can be added to $C_h$ as an investment to keep products in conforming conditions. Also, the cost of water pollution $C_{WP}$ can be added to the holding cost as a shared cost between the supplier and the retailer. Figure 5 presents the adapted $(Q, R)$ model with these four SD cost variables:

The last two cost variables, $C_{PR}$ and $C_{DW}$ are considered to be dependent on the lot size. Thus, these are integrated into the total cost formulation of the $(Q, R)$ model as described below:

$$\begin{aligned} \text{TC} = {} & \text{total order cost} + \text{total holding cost of cycle inventory} \\ & + \text{total holding cost of safety stock} \\ & + \text{total shortage cost} - \text{total incentive for reuse} \\ & \quad \text{of products} + \text{total disposal cost of waste}, \end{aligned} \tag{2}$$

where

(a) Total order cost $(\text{TC}_o) = (C_o \times D)/Q$

(b) Total holding cost of cycle inventory $(\text{TC}_h) = (C_h \times Q)/2$

Table 5: AHP weights obtained for the interactions between all criteria, subcriteria, and alternatives (own work).

| Goal | Consistency ratio | Criteria/factors L1 | L2 | Alternatives L3 | | | | |
|---|---|---|---|---|---|---|---|---|
| Definition of SD criteria that impact inventory through the SC | 0.0516 | Eco 0.5936 | Eco_Q 0.2234 | A_Eco_Q1 0.0075 | A_Eco_Q2 0.0269 | A_Eco_Q3 0.0375 | A_Eco_Q4 0.0568 | **A_Eco_Q5 0.0947** |
| | | | Eco_E 0.0887 | A_Eco_E1 0.0026 | A_Eco_E2 0.0045 | A_Eco_E3 0.0159 | A_Eco_E4 0.0213 | **A_Eco_E5 0.0443** |
| | | | Eco_R 0.2815 | A_Eco_R1 0.0366 | A_Eco_R2 0.0895 | **A_Eco_R3 0.1114** | A_Eco_R4 0.0245 | A_Eco_R5 0.0165 |
| | 0.0176 | Env 0.2493 | Env_E 0.0523 | A_Env_E1 0.0024 | A_Env_E2 0.0035 | A_Env_E3 0.0133 | **A_Env_E4 0.0267** | A_Env_E5 0.0065 |
| | | | Env_N 0.0599 | A_Env_N1 0.0028 | A_Env_N2 0.0089 | **A_Env_N3 0.0288** | A_Env_N4 0.0036 | A_Env_N5 0.0158 |
| | | | Env_W 0.1371 | A_Env_W1 0.0076 | A_Env_W2 0.0069 | A_Env_W3 0.0368 | **A_Env_W4 0.0496** | A_Env_W5 0.0362 |
| | 0.0036 | Soc 0.1571 | Soc_H 0.0172 | A_Soc_H1 0.0010 | A_Soc_H2 0.0046 | A_Soc_H3 0.0009 | A_Soc_H4 0.0045 | **A_Soc_H5 0.0062** |
| | | | Soc_W 0.0485 | **A_Soc_W1 0.0298** | A_Soc_W2 0.0057 | A_Soc_W3 0.0130 | | |
| | | | Soc_E 0.0913 | A_Soc_E1 0.0061 | A_Soc_E2 0.0028 | A_Soc_E3 0.0212 | A_Soc_E4 0.0157 | **A_Soc_E5 0.0455** |

Table 6: Interpretation of results of the AHP analysis presented in Table 5 (own work).

| Goal | Criteria/factors L1 | L2 | Final results (most significant alternative) |
|---|---|---|---|
| Definition of SD criteria that impact inventory through the SC | Economic 0.5936 | Quality 0.2234 | Customer satisfaction 0.0947 |
| | | Efficiency 0.0887 | Inventory costs 0.0443 |
| | | Responsiveness 0.2815 | Lead time 0.1114 |
| | Environmental 0.2493 | Emissions 0.0523 | Level of $CO_2$ emission from transport processes 0.0267 |
| | | Natural resources 0.0599 | Energy consumption/revenue 0.0288 |
| | | Waste and recycling 0.1371 | Level of products reused 0.0496 |
| | Social 0.1571 | Health and safety 0.0172 | Toxic and hazardous emissions 0.0062 |
| | | Waste 0.0485 | Water pollution 0.0298 |
| | | Employees 0.0913 | Disposal of work waste 0.0455 |

(c) Total holding cost of safety stock ($TC_h\_SS$) = $C_h \times [R - \mu_{LT} + \sigma_{LT} L(z)]$

(d) Total shortage cost (TC_shortage) = $C_{LT} \times (D/Q)$

(e) Total incentive for reuse of products $(TC_{PR}) = gQ \times (D/Q) = C_{PR} \times (D/Q), 0 < g < 1$

(f) Total disposal cost of waste $(TC_{DW}) = rCQ \times (D/Q) = C_{DW} \times (D/Q), 0 < r < 1$

## 5. Assessment of the Model

The textile industry is one of the most important manufacturing industries. However, it is also one of the industries that have a more negative impact on the environment and social welfare. In this case, the proposed model can be used to reduce the costs associated with these impacts.

Let us consider the inventory production and distribution of cotton t-shirts of 250 grams. Based on the feedback obtained from two retailers, the annual demand for this product was estimated as $D = 40000$ units with a delivery cost of 100 USD/lot ($C_o$).

For this product, the associated cost elements of the integrated model were estimated as follows (the same methodology can be performed for different products):

(i) Quality is assured by the implementation of diverse processes and personnel. According to [24], the salary of a quality engineer is approximately 700 USD per month. In practice, approximately 20% of the products are sampled for quality control. This leads to approximately $0.20 \times (40000 \text{ units}/12 \text{ months}) = 667$ units per month. Considering that sampling represents approximately 30% of the activities performed by the quality engineer, the unit cost of quality $C_Q$ is estimated as $(0.30 \times 700 \text{ USD})/667$ units = 0.32 USD/unit

(ii) The unit cost $C$, which considers raw material and production costs, averages 3.0 USD/unit [25].

(iii) Holding cost $C_h$ is minimal as t-shirts do not require specific warehousing conditions. It is estimated as 0.05 USD/unit

Table 7: Top six SD cost variables for inventory management (own work).

| | | |
|---|---|---|
| Economic | Quality | $C_Q$ |
| | Lead time | $C_{LT}$ |
| Environmental | Level of $CO_2$ emission from transport processes | $C_E$ |
| | Level of products reused | $C_{PR}$ |
| Social | Water pollution | $C_{WP}$ |
| | Disposal of work waste | $C_{DW}$ |

(iv) Nowadays, some countries have a tax policy to regulate the contamination of water caused by textile manufacturing [26]. For this case, a t-shirt requires approximately 2,700 liters of water or 2.7 cubic meters [27]. If the task averages 0.20 USD/m$^3$, $C_{WP}$ is approximated as $(0.20 \text{ USD/m}^3) \times (2.7 \text{ m}^3/\text{unit}) = 0.54$ USD/unit

(v) It is expected that manufacturers perform the appropriate measures to dispose of waste. Collecting and disposing of a batch of combined waste approximately costs 400 USD/ton [28]. In this case, a cost of 80 USD is considered for $C_{DW}$

(vi) Reused products can be considered as refurbished or substitution products. In practice, this accounts for approximately 5% of a lot. Thus, $C_{PR} = 0.05 \times (C - \text{refurbished cost}) \times Q = 0.05 \times (3.0 - 2.0)$ USD $\times Q = 0.05Q$ USD

(vii) For a stock-out unit of product, a cost $p = 1.5C$ is considered due to loss and additional penalties. This leads to define $C_{LT} = 1.5 \times 3 \times K = 4.5K$ USD

(viii) To estimate $C_E$, it is important to determine the transportation route from the (supplier) manufacturer to the seller (retailer). Figure 6 presents an example of the route with a length of 375 km. Based on the work reported in [29], for a standard vehicle with a cargo capacity between 1.305 tons and 1.740 tons, an emission of 225 g$CO_2$/km is generated if diesel is consumed. This leads to an estimate total of 85.0 kg$CO_2$ for the trip. In practice, an emission

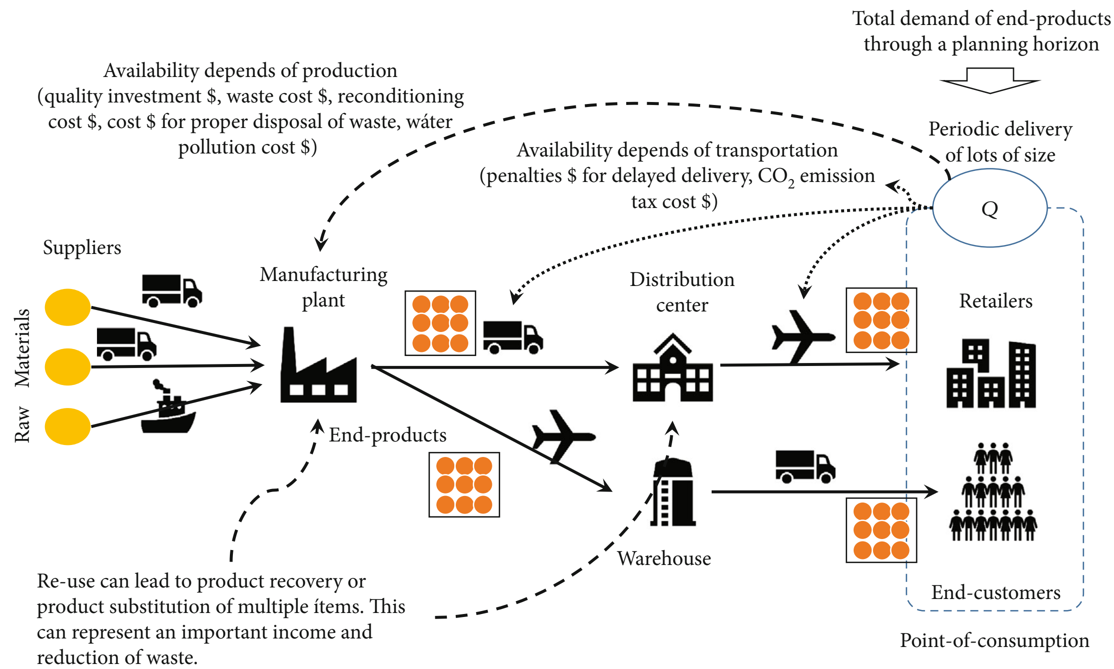


Figure 3: Economic aspects of the SC associated to inventory control.

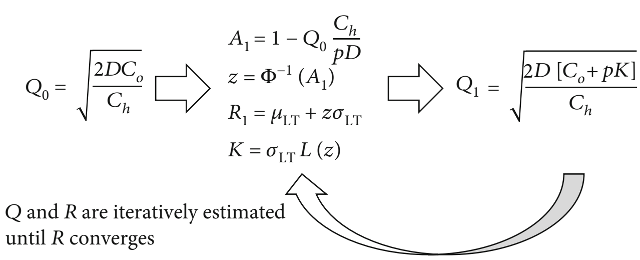


Figure 4: Estimation process of the inventory control policy under the $(Q, R)$ model [23].

tax is established to try to reduce $CO_2$ emissions. In this case, a reference of 0.0020 USD per $gCO_2$/km, this results in $C_E = (225\ gCO_2/km) \times (0.0005\ USD\ per\ gCO_2/km) \times (375\ km) = 42.1875\ USD$

Table 8 presents the overview of the previously defined cost variables together with the additional variables for the $(Q, R)$ model. As the lead time is defined in days, a reference of daily demand is considered for $\mu_{LT}$ and $\sigma_{LT}$. Also, as uncertain demand is considered, a coefficient of variability of 25.0% is assumed.

On the other hand, Table 9 presents the results of the iterative process for the estimation of $Q$ and $R$. As presented, convergence is achieved on the 3rd iteration. With this result, where $Q = 3568$ units and $R = 1307$ units, $C_{PR} = 0.05 \times 3568 = 178.40$ USD. If no costs associated with SD criteria are considered, the following results are obtained: $Q = 12677$ and $R = 1360$. In such cases, $R$ does not change significantly; however, $Q$ increases by a factor of 3.55. This is expected because if SD criteria are to be considered, more care must be taken to establish the economic lot.

Table 10 presents the total cost analysis for both scenarios. As presented, even though the SD model has more costs due to waste disposal and order costs with $CO_2$ emissions and quality assurance, one significant income may come from investment in product reuse. This practice can represent a higher incentive which can compensate for the other SD costs. This is an improvement on the standard case where product reuse is not performed.

## 6. Conclusions and Future Work

An important aspect to perform SD practices is the economic effort needed for their implementation. As discussed, there are specific SD factors associated with inventory control that must be carefully managed in order to maintain economic benefit.

For this purpose, six SD cost variables were identified and modelled within the $(Q, R)$ model for assessment of their impact and outcomes of their implementation. As discussed by other works, implementation of SD practices can increase the costs of the company significantly. This was observed in the analysis presented in Table 10. Particularly, those associated with lots (i.e., emission cost due to transportation and waste management) represent the highest costs. However, the opportunity of product reuse can lead to significant economic benefits which can compensate these costs. This can also lead to important advantages over standard practices where SD criteria are not considered.

Even though these results lead to define specific practices to obtain economic benefits from SD factors, additional work must be performed to extend on the analysis and identification of other SD criteria. In example, stored inventory can lead to emission of contaminants which can affect the workers' health. Thus, this should be considered within the

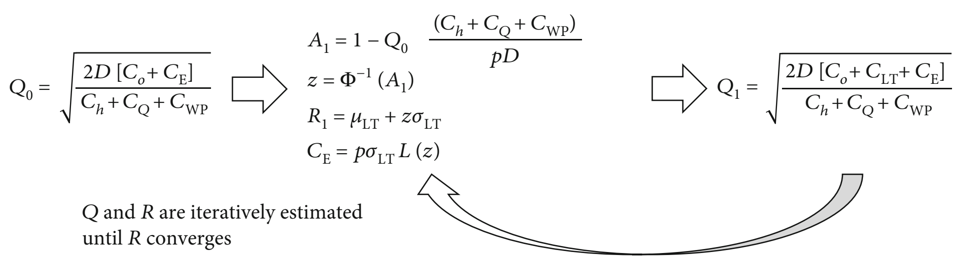


Figure 5: Estimation process of the inventory control policy under the adapted (Q, R) model with four SD cost variables (own work).

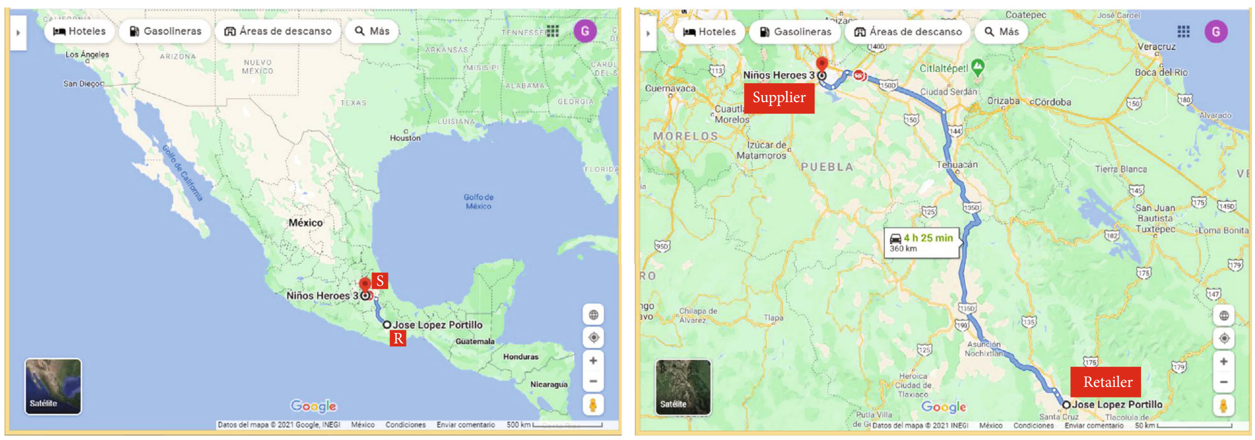


Figure 6: Route between supplier and retailer for the estimation of $C_E$.

Table 8: Overview of cost variables for the (Q, R) model with SD criteria.

| | | | | | |
|---|---|---|---|---|---|
| $D$ | 40000 | Units | $C_h$ | 0.05 | USD per unit |
| Days | 360 | | $C_O$ | 100.00 | USD per lot |
| $d$ | 112 | Units | $C_E$ | 42.19 | USD per lot |
| $\sigma$ | 28 | Units | $C_Q$ | 0.32 | USD per unit |
| LT | 10 | Days | $C_{WP}$ | 0.54 | USD per unit |
| $\mu_{LT} = d \times LT$ | 1120 | Units | $C_{DW}$ | 80.00 | USD per lot |
| $\sigma_{LT} = \sigma\sqrt{LT}$ | 89 | Units | | | |
| $C$ | 3.00 | USD per unit | | | |
| $p$ | 4.50 | USD per unit | | | |

Table 9: Results of the (Q, R) model with SD criteria.

| | | $A$ | $z$ | | | $L(z)$ | $K = \sigma_{LT} L(z)$ | $C_{LT}$ |
|---|---|---|---|---|---|---|---|---|
| $Q_0$ | 3536 | 0.9821 | 2.10 | $R_1$ | 1307 | 0.0065 | 0.58 | 2.59 |
| $Q_1$ | 3568 | 0.9820 | 2.10 | $R_2$ | 1307 | 0.0065 | 0.58 | 2.62 |
| $Q_2$ | 3568 | 0.9820 | 2.10 | $R_3$ | 1307 | 0.0065 | 0.58 | 2.62 |
| $Q_3$ | 3568 | 0.9820 | 2.10 | $R_4$ | 1307 | 0.0065 | 0.58 | 2.62 |
| $Q_4$ | 3568 | 0.9820 | 2.10 | $R_5$ | 1307 | 0.0065 | 0.58 | 2.62 |
| $Q_5$ | 3568 | 0.9820 | 2.10 | $R_6$ | 1307 | 0.0065 | 0.58 | 2.62 |
| $Q_6$ | 3568 | 0.9820 | 2.10 | $R_7$ | 1307 | 0.0065 | 0.58 | 2.62 |

Table 10: Comparison of total annual costs of the (Q, R) model with SD criteria and the standard (Q, R) model.

| | (Q, R) SD model | (Q, R) model |
|---|---|---|
| $TC_o$= | 1121.08 | 315.53 |
| $TC_h$= | 89.20 | 316.93 |
| $TC_h$_SS= | 9.38 | 12.00 |
| TC_shortage = | 29.36 | 1.36 |
| $TC_{PR}$= | 2000.00 | |
| $TC_{DW}$= | 896.86 | |
| Annual total inventory cost = | 145.88 | 645.82 |

lot ordering process. Also, considering other inventory models can lead to improve the applicability in other industries.

## Data Availability

The data used for the present work is described in the manuscript. Where applicable, other sources have been referenced.

## Conflicts of Interest

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

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