Chapter

Modeling the Hidden Risk of Polyethylene Contaminants within the Supply Chain

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Abstract

Inventory management is very important to support the supply chain of the manufacturing and service industries. All inventories involve warehousing; however, most of the products and packages are associated to plastic which is the main generator of polyethylene (phthalate) pollution in the air and water resources. In fact, phthalate has been identified as the cause of serious health conditions and its impact within the operation of logistic processes has not been studied. In this work, we perform research on the generation of phthalate as the control on these emissions is important to adjust the supply strategy to reduce the human risk exposure and contamination of the environment. For this purpose, generation of phthalate is modeled through the use of artificial neural networks (ANNs) and its impact on the supply strategy is assessed through its integration within a stochastic inventory control model. As presented, it is possible to adjust the supply strategy to reduce the cumulative generation of phthalate within the warehouse and thus reduce its impact on human health and environment sustainability.

Keywords: sustainability, phthalate contamination, inventory control, supply strategy, artificial neural networks

1. Introduction

An important aspect to consider for sustainable proposals is the growth of the world population, which is projected to increase from 7 to 9 billion people by the year 2050 [1, 2]. This is a challenge for companies to comply with economic, environmental, and social needs.

As presented in **Figure 1**, to address economic, environmental, and social issues, companies must address multidisciplinary issues such as follows:

- sustainable development (SD) which emphasizes the balance between economic well-being, natural resources, and society without compromising the quality of life of the human population [3];
- supply chain (SC) management, which is focused on optimizing the flow of goods and services through the supply chain, considering the procurement of

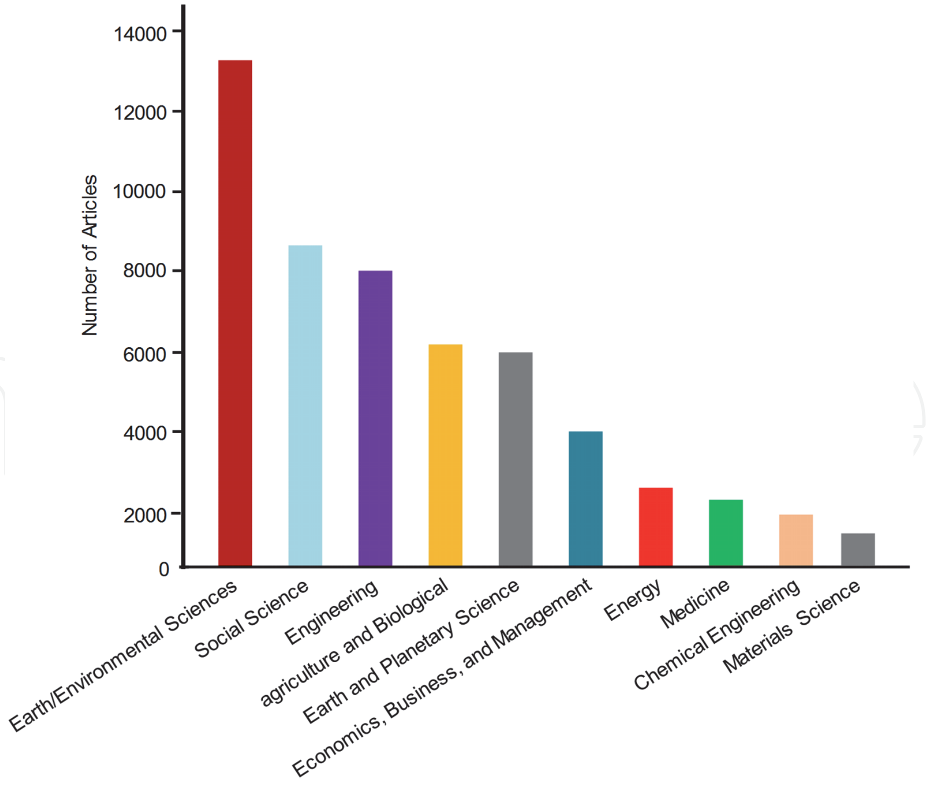

Figure 1.
Interdisciplinary studies in sustainability (adapted and edited from Ref. [4]).

raw materials, the distribution from suppliers to manufacturers, the transformation into final products and warehousing operations, and the distribution of final products from manufacturers to retailers. This to actively streamline the company's supply-side activities to maximize customer value and gain a competitive advantage in the marketplace.

- inventory control and management, which is focused on determining the appropriate inventory replenishment strategies to ensure efficient supply and distribution of products when needed at the minimum cost.

Here, it is important to observe that different storage/warehousing is performed through all the SC. Just in the last decade, health risk was identified for people who work at storage facilities due to the presence of semi-volatile organic compound pollutants (SVOC) and plastic contaminants which are generated by the stored inventory [5–7]. In this regard, the most abundant SVOCs found among the 58 classified SVOCs are phthalates.

In general, there are six types of phthalate that have been found in outdoor and indoor air and surfaces [6, 8]. Phthalates are distributed worldwide, having a global presence ranging from the most remote regions in the Arctic to isolated rainforests of the Amazon [8, 9]. On March 2019, the United States Environmental Protection Agency (EPA) issued a priority list of 40 chemicals to determine if they are of high or low risk for human health. Phthalates were considered within the "high priority" list [6].

There are studies that have concluded that the pollution of phthalate in the air is harmful to human health [8–12]. Also, it has been determined that humans are exposed through ingestion, inhalation, and dermal exposure, even since intrauterine development [13, 14].

Because phthalates, which are organic lipophilic compounds, are mainly used to increase the flexibility of plastic polymers, they are frequently used in printing inks

Country	Place	Work
Japan	Home	[19]
China	Home/office	[20]
Sweden	Pre-school	[21]
Canada	Home	[22]
USA (California)	Child care facility	[23]

Table 1.
Research works performed on indoor phthalate (taken from Ref. [8]).

and food packages [14, 15]. Thus, exposure to phthalates mainly occurs via food ingestion [10, 14, 16–18].

Inhalation is the second route of exposure as phthalates degrade into particles that diffuse through the air [10]. This can be the main route of exposure for individuals who work in plasticizing processes [10] or in closed places where products with phthalate are stored for long periods of time such as in warehouses. Because phthalates are used as plasticizers in numerous consumer products, commodities, and building materials, this compound has been found in offices, work places, homes, bathrooms, gardens, and food containers. **Table 1** presents an overview of the places where people are more exposed to indoor phthalates.

As presented in **Table 1**, phthalates are found in human residential and occupational environment in high concentrations, both in air and in dust [24]. Thus, we can consider the facilities of industries such as warehouses, productions areas, and scrap areas, to be frequently contaminated with this compound.

In the case of products which are stored during long periods of time, there are economic, environmental, and health implications on SD. If the product is not used or moved (e.g., low inventory rotation), it may deteriorate and/or become obsolete, leading to economic losses. Also, a deteriorating product may release other harmful chemicals. Finally, in the social aspect, there is the health risk for employees who are exposed to harmful chemicals generated by the stored products. If the management fails to determine the optimal inventory levels and lots, the environmental, social, and economic risks can affect all entities through the SC.

To extend on these findings, we perform an updated review of the presence of phthalates and their effect on human health. Also, we extend on the adaptation of supply strategies to reduce these effects through the SC and on the environment. This is performed through the modeling of phthalate generation and integration within a stochastic inventory control strategy.

2. Pollution related to phthalates

Phthalates are chemicals which are produced in high volumes, accounting for 70% of the world consumption of plasticizers in 2014. In this context, Asia, Western Europe, and the USA accounted for 59, 14, and 16%, respectively, of the world plasticizer consumption in 2014 [25].

More recently, phthalates accounted for 65% of the world consumption of plasticizers in 2017. **Figure 2** presents the main consumers of plasticizers in 2017. However, in 2005, this amount was higher (approximately 88%), and it was forecasted to decrease to 60% by 2022. This decrease was defined to be caused by [25]:

- rapid consumption growth of non-phthalate plasticizers, mainly terephthalates, epoxy, aliphatics, and benzoates, as replacements for DEHP and other phthalates such as DINP and BBP;

- continued growth of non-phthalates in different applications and markets; and

- ongoing pressure from retailers and consumers to limit the use of phthalates, especially in developed regions.

However, consumption of phthalate plasticizers has been also forecasted to grow at an average annual rate of 1.3% during 2017–2022. Today, phthalates are known pollutants, which can affect human health. Human bio-monitoring studies from 2000 to 2015 have determined that exposure to phthalates can cause adverse health outcomes like fertility problems, respiratory diseases, childhood obesity, and neuropsychological disorders [9, 12, 15, 26]. Other studies found that it may disrupt fetal testicular testosterone production [27, 28].

Although many studies have researched on the impact of outdoor pollution on human health, few studies have investigated the impact of indoor pollution on the human health. Because people spend most of their time indoors, it is crucial to understand how an indoor pollutant, including household dust, affects human health [19, 29].

Indoor pollution is largely influenced by outdoor sources, but indoor activities (e.g., cooking, cleaning, and the use of consumer products and building materials) are also sources of indoor pollution [5, 11, 20, 23, 30, 31]. Phthalate levels build up over time in indoor environments where their main sources like children's toys, cosmetics, flexible PVC flooring, and cable insulation among others are found [8, 31].

Consequently, six phthalates, namely, dimethyl phthalate (DMP), diethyl phthalate (DEP), di-n-butyl phthalate (DBP), butyl-benzyl phthalate (BBP), di(2-ethylhexyl) phthalate (DEHP), and di-n-octyl phthalate (DnOP) have been identified as priority pollutants by the United States Environmental Protection Agency

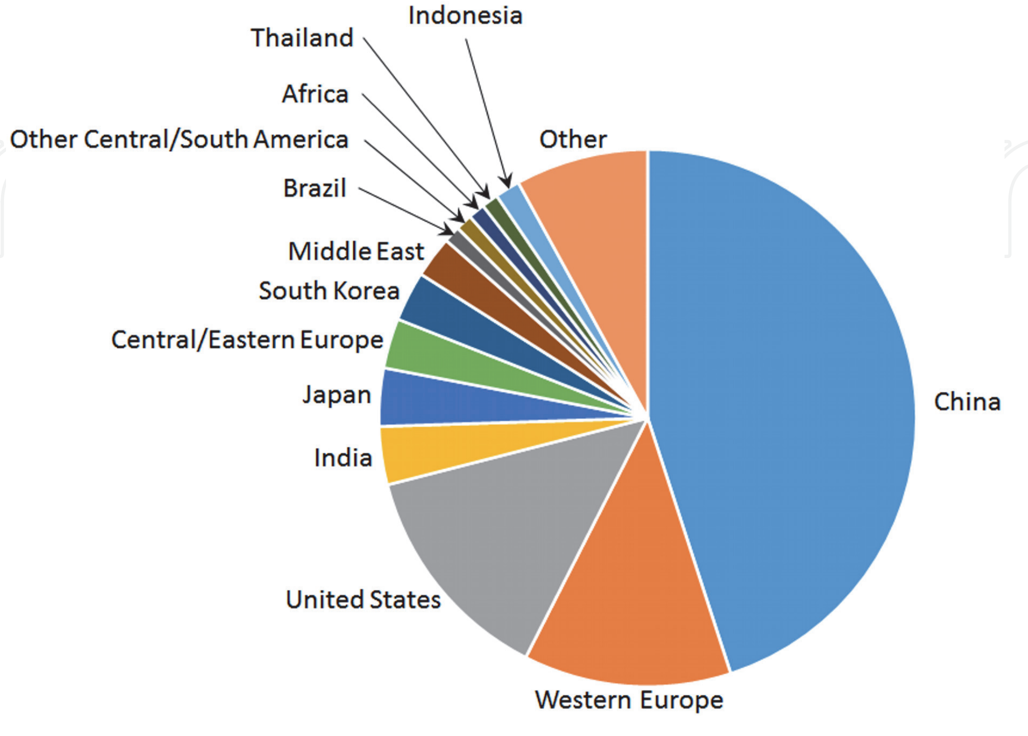

Figure 2.
World consumption of plasticizers 2017 (adapted and edited from Ref. [25]).

(US EPA) and the European Union (EU). Usage of DEHP, DBP, BBP and DnOP has been limited to ≤0.1% in toys and childcare articles by EU (Directive 2005/84/EC), US (CPSIA—Consumer Product Safety Improvement Act of 2008), China (China National Standard GB 6675, 2014), India (BIS, 2011), and Japan (Japan Toy Safety Standard ST-2002 Part 3, 2011). Recently in 2015, DEHP, DBP, and BBP were classified as reproductive toxicant category 1B and completely banned from any application without prior approval in the EU.

To compare two exposure scenarios, different dust particle fractions were analyzed: inhaled (<5 μm) and ingested (<75 μm) fraction sizes. Results showed that the daily intake of dust-contaminated phthalate was 2 to 12 times (inhalation and ingestion, respectively) higher for 2-year-old children than for adults [11].

However, phthalate exposure (phthalate metabolite levels in urine) among countries indicates the highest exposure for people living in Europe (2.1×10^2 μg/l) closely followed by USA (2.0×10^2 μg/l) and least in Asia (1.3×10^2 μg/l) [26]. In this context, there are reported discrepancies between trends of industrial consumption and human exposure [8, 14, 18].

The highest concentrations of phthalates in different items have been found in the range of 300–461 g/kg for DEHP, 283–345 g/kg for DBP, 150 g/kg for DnOP, and 20–33 g/kg for BBP in floorings, shower curtains, gloves, plastic sandals, plastic balls, and soap packaging [8, 18].

Particularly in Latin America, a phthalate presence study was carried out on beverages, where the results brought that the bottles contained average 2.62 g/kg of diethylhexyl (FDEH) [10, 32].

Increased phthalate levels have been found in the presence of temperature changes (i.e., bottled water exposed to higher than 35°C or sunlight) [31, 33–35]. Elevated temperatures considered in various studies do not represent ambient temperature but become important in case of heating of for example food in products containing phthalates. However, the influence of temperature on phthalate emissions in dust requires further investigation.

Also, higher relative humidity has been reported to increase hydrolysis of phthalates, which results in a gradual decrease in concentration of phthalates in the source and a sink [8]. An increase in temperature increases the emission rates of non-covalently bound phthalates from their polymer matrices resulting in a higher concentration in warmer months [30]. In good agreement, studies have found higher phthalate levels in summer in indoor as well as outdoor surfaces [8, 9].

These studies have been carried out in houses, kinder gardens, and offices in places where cleaning is regular [8, 15]. Hence, in closed places where products with this chemical are stored, the toxicity risk is even higher. Thus, there is a necessity to reduce the effect of this chemical by storing just the optimal lots.

3. Where the phthalates are within logistic facilities and what can we do?

Within all industries, management is focused on solving the essential decision-making associated to product design/placement, organization, picking operations, facility layout, and distribution. These operations take place within spaces or logistic facilities such as offices, workshops, and warehouses, where workers spend most of their time (40–60 hours per week). In these closed places, airflow distributes many impurities, including phthalates which can be ingested or inhaled [9, 14, 15, 32].

The importance of airflow has been studied when designing the warehouses because phthalates are not chemically bound to the plastics and they can leach into

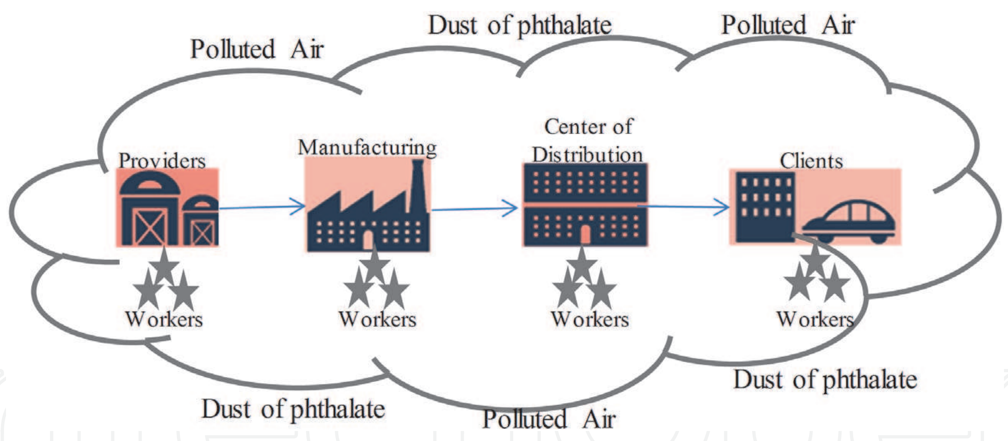

Figure 3.
Theoretical exposure of phthalates through the air (own work).

water, indoor dust, and air, resulting in cyclic exposure [14, 36]. In these closed spaces, the stored products can spread out this pollutant which may be increased based on temperature conditions. In this situation, co-workers inhale phthalates during labor time [14, 15] and contamination by phthalates (more than 100 mg/l) has been reported to be common in heavily industrialized areas.

Additional to airflow, inventory movement is another aspect to contribute to phthalate accumulation. As inventory commonly stores packaged products (bottles, bags, paper and board packaging, etc.) if it remains static, it can generate more dust and particles [9–11, 32]. Based on this information, **Figure 3** presents the theoretical cycle of emission of phthalate within the facilities present in the SC.

From this cycle of emission, we can identify that inventory movement through the facilities is dependent of the inventory turnover, which can be optimized through the use of proper supply strategies. This task requires consideration of real market conditions which are characterized by demand of products with large variability.

Thus, stochastic demand patterns are a main aspect to consider within the strategies to reduce phthalate accumulation/emission and improve inventory turnover.

4. Modeling the phthalate emission within the supply strategy

Within logistic management of inventories, there are strategies to improve inventory turnover and reduce static inventory and inventory levels. As an example, consider the cost equation of the continuous review strategy to determine the optimal lot size Q of inventory to reduce operational costs [37]:

$$E(C) = \frac{DC_o}{Q} + \frac{C_hQ}{2} + C_h[R - \mu_{LT} + \sigma_{LT}L(z)] + \frac{pAD}{Q}, \tag{1}$$

where C_o is the order cost per lot, C_h is the holding cost per unit within Q, p is the unit stock-out cost, D is the cumulative demand through a planning horizon, μ_{LT} and σ_{LT} are the mean and standard deviation of the demand during the lead time, $L(z)$ is the standard loss function with $z = \Phi^{-1}(1 - (QC_h)/(pD))$, and A is the expected stock-out units per inventory cycle ($=\sigma_{LT}\, L(z)$).

As emission of phthalates is associated to the size of the warehoused lot (i.e., Q), this aspect can be integrated into this strategy to determine a more appropriate lot size. For this purpose, consider that $f(t)$ is the general emission function of phthalate through time t per stored unit and H is the maximum safety level of phthalate within a closed space. In this case, the cumulative generation of phthalate through time associated to the average stored lot Q then can be estimated as follows:

$$\frac{Q}{2}\int_{0}^{t} f(t). \tag{2}$$

To determine the optimal lot size considering the minimization of phthalate, the following mathematical formulation can be defined:

$$Minimize\ E(C) = \frac{DC_o}{Q} + \frac{C_h Q}{2} + C_h[R - \mu_{LT} + \sigma_{LT}L(z)] + \frac{pAD}{Q} \tag{3}$$

Subject to:

$$\frac{Q}{2}\int_{0}^{t} f(t) \leq H, \tag{4}$$

$$Q \in \Re^{+}, \tag{5}$$

where (3) is the objective function, (4) is the restriction to ensure that the lot size does not lead to increase the cumulative phthalate over a permissible limit H, and (5) is the restriction over Q to consist of real positive values.

Additionally, periodic surface cleaning and handwashing has been identified as appropriate measures to reduce accumulation and exposure to phthalate [38]. Particularly for co-workers, the use of protective wear within warehouses is highly recommended.

Research performed to model *f(t)* has led to different proposals and values. This is understandable due to the different considered environments and contexts (i.e., home, office, plants, etc.). As we are concerned regarding the applicability of the model in the supply strategy, we propose a general emission model that can be adapted to different contexts by the use of artificial neural networks (ANNs).

The advantage of ANNs to model data when compared to standard regression approaches is that regression only performs well if the regression equation fits very closely the considered data. By contrast, the use of hidden neuron layers provides ANNs with more flexibility to fit any data pattern.

As input data for modeling, we considered the estimations presented by Afshari et al. and Liang et al. [39, 40] regarding phthalate concentrations (μg/m^3) generated by PVC and different materials in indoor spaces. **Figure 4** presents a review of the approximate concentration values reported in Refs. [39, 40].

As presented in **Figure 4**, significant differences are found depending on the considered material and environment. For assessment purposes of the proposed model, we consider an average concentration which is also presented in **Figure 4**.

For modeling through ANNs, it was important to match the concentration data based on m^3 to stored units in the warehouse. To accomplish this task, the following variables are considered:

V_Q = volume (m^3) associated to each product unit and E_t = cumulative emission per m^3 associated to a product unit at a time t.

Thus, (4) can be represented as:

$$\frac{Q}{2}\int_{0}^{t} f(t) \leq H \rightarrow \frac{Q}{2} \times V_Q \times E_t \leq H, \tag{6}$$

where E_t is obtained through the regression achieved with ANNs.

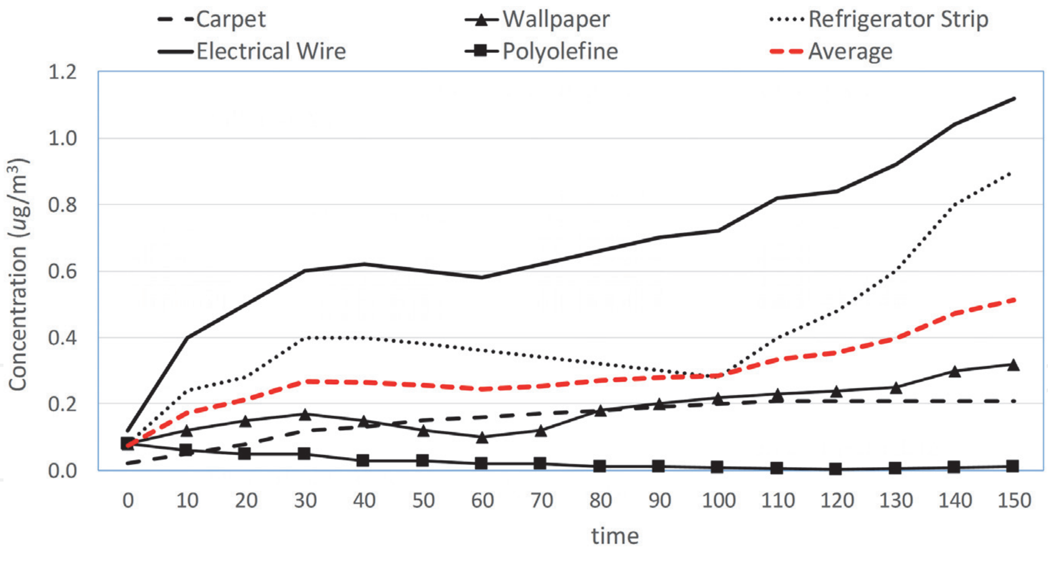

Figure 4.
Review of concentration patterns through time on different indoor spaces and materials (own work based on data reported in Refs. [39, 40]).

For this purpose, we considered the nonlinear autoregressive with external (exogenous) input (NARX) [41] time series ANN. For time series modeling, the NARX ANN can associate the current value of a time series to (a) past values of the same series and (b) current and past values of an external series that influences the series of interest [42]. Thus, it can predict a series $y(t)$ given n past values of $y(t)$ and another series $z(t)$. This is leads to more accurate modeling when compared to nonlinear input-output ANNs.

In this case, $z(t)$ is the time series (in days) and $y(t)$ is the cumulative average concentration ($\mu g/m^3$). Implementation of the NARX ANN was performed with the MATLAB R2016a software on a DELL laptop computer with Intel i7 CPU at 2.06 GHz and 8 MB RAM. **Table 2** and **Figure 5** present the details of the ANN and the training algorithm.

Figure 6 presents the comparison of the performance of the ANN for t = 0:360 days and the original average data with t = 0:150 (as presented in

Hidden layers	2
Neurons	10
Training method	Levenberg-Marquardt

Table 2.
Training details of the NARX ANN.

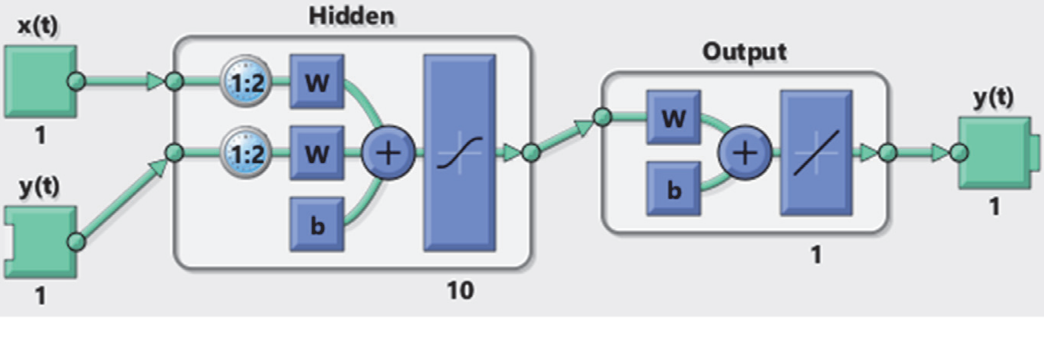

Figure 5.
Structure details of the NARX ANN.

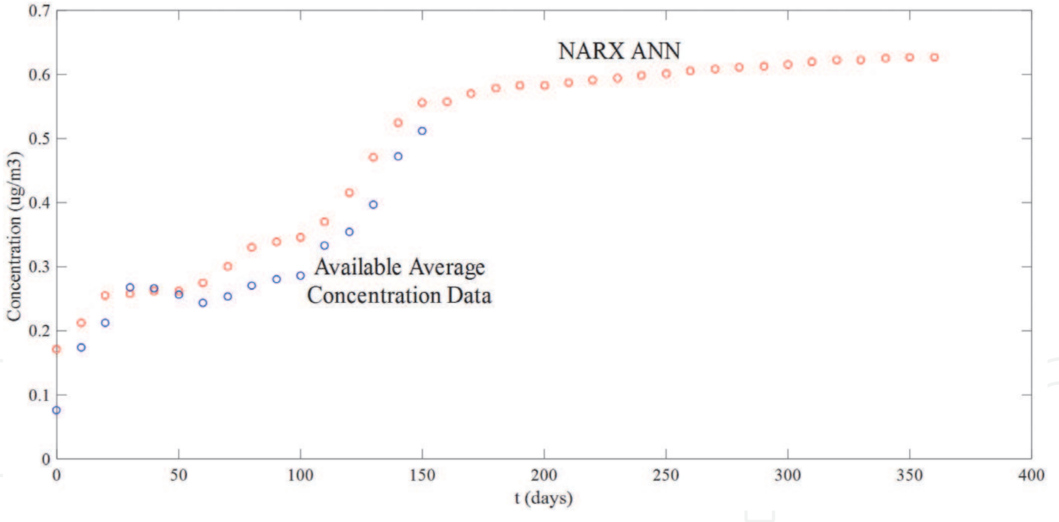

Figure 6.
Performance of the NARX ANN for extended time periods.

Figure 4). It can be observed that the prediction of the ANN closely resembles the available data used for training within the period from t = 0:150 days.

With the estimated concentrations, we can proceed to assess the model described by (3)–(6) with a supply example. This assessment considers two scenarios: (a) scenario with no control on the phthalate concentrations and (b) scenario with restriction *H* on the phthalate concentration per inventory cycle. These details of this assessment are presented in the following section.

5. The economic and environmental impacts of phthalate emission control within the supply strategy

In the previous section, we provided the means for phthalate concentration modeling through ANNs and its integration within an inventory supply strategy. To address the impact of this strategy, we proceed to quantitatively evaluate the economic and environmental results on an inventory supply case.

Table 3 presents the numerical data of the considered supply case (this is, the set of values for (3)–(6)). This case considers the supply strategy over a 5-year period (1800 days with a cumulative demand of 60,000 units). Each unit of product is assumed to have a standard size of 0.50 m × 0.50 m × 0.50 m = 0.125 m^3. At t = 250 days, the cumulative concentration is expected to be at 0.61 μg/m^3 and an estimate of H = 50.0 μg/m^3 is considered as a safety limit.

Planning horizon = 1800 days	D = 60,000 units
C_o = 340 USD	Daily demand = D/1800 = 60,000/1800 = 34 units
C_h = 12 USD	Daily standard deviation = 8 units
Lead time = 180 days	p = 45 USD
V_Q = 0.125 m^3	t = 250 days
H = 50.0 μg/m^3	$E250$ = 0.61 μg/m^3

Table 3.
Assessment data for the integrated model with phthalate emission.

Scenario	1	2
Objective function	$Minimize\ E(C) = \frac{DC_o}{Q} + \frac{C_h Q}{2} + C_h[R - \mu_{LT} + \sigma_{LT} L(z)] + \frac{pAD}{Q}$	
Restrictions	Q > 0	Q > 0 $\frac{Q}{2} \times V_Q \times E_t \leq H$
Q	1880	1312
R	6257	6271
$E(C)$	25,646	27,088
$\frac{Q}{2} \times V_Q \times E_t$	71.66 μg/m^3	50.00 μg/m^3

Table 4.
Results of the integrated model with the assessment data.

With these data, we proceed to evaluate two scenarios:

a. Scenario 1: determination of the supply lot size Q is performed based only on the economic aspects of (3) without the phthalate emission factor.

b. Scenario 2: determination of the supply lot size Q is performed based on the economic aspects of (3) and considering the phthalate emission factor defined by (4) and (6).

Both scenarios were solved with the Solver Tool ® of MS Excel. The results which were obtained are presented in **Table 4**.

If no restriction on the concentration of phthalate is considered, then large lots can be ordered (Q = 1880 units). This minimizes the overall operating costs (E(C) = 25,646). Also, these large lots can lead to cumulative phthalate concentration up to 71.66 μg/m^3.

If the restriction on the cumulative phthalate is considered, a reduction of 30.22% can be obtained (50.00 μg/m^3). However, as this is dependent of the lot size, smaller lot sizes are required (Q = 1312 units). As consequence, this can lead to an increase in operational costs up to 5.62% (E(C) = 27,088).

These findings are very important to establish strategies to balance economic and environmental/health benefits. Particularly within the supply chain, suppliers, manufacturers, and distributors are continuously exposed to phthalates and thus represent health risks in the long term.

6. Conclusions

Minimizing the exposure to phthalate is an important task within all contexts in our society. These chemicals are present in office buildings, schools, homes, vehicles, food packaging, and warehouses, among others. The sources of phthalates which are used in building materials are more permanent in nature and their removal requires regulatory intervention, while other sources such as plastic materials and foam mattresses are easier to be replaced or removed [8].

In manufacturing, where inventories are the main resource for production, supply, and distribution, phthalates are continuously present. However, determining the possible risk based on phthalate concentration through time in warehousing facilities is not widely studied.

In this work, we explored on this aspect and proposed an integrated inventory control model with phthalate emission factor. Also, we addressed phthalate emission through the use of ANNs to estimate concentrations for different time periods where are commonly considered during inventory control strategies.

As presented, if phthalate concentrations are not considered, these can be increased in the presence of large lots, which frequently decrease operational costs associated to inventory ordering/re-supply.

If considering the phthalate concentration restriction to a certain permissible level, this can lead to reduce the ordering lots and, thus, to increase the operational costs. Nevertheless, the cost increase may be minimal in comparison to the reduction in phthalate concentration.

Thus, the proposed model can be used to support measures to control the presence of phthalate while keeping also under control the operational costs. Also, the model can be used as a basis for extended or alternative models considering the costs of cleaning tasks and the risk of specific health complications in certain environments/contexts.

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