Omega 88 (2019) 110–132

Contents lists available at ScienceDirect

Omega

journal homepage: www.elsevier.com/locate/omega

Robust design of a closed-loop supply chain under uncertainty conditions integrating financial criteria

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ARTICLE INFO

Article history:
Received 30 December 2017
Accepted 10 September 2018
Available online 14 September 2018

Keywords:
Economic value added
Closed-loop supply chain
Robust design
Electronics industry

ABSTRACT

This paper proposes the formulation of a Mixed Integer Non-Linear Programming (MINLP) model that integrates financial risks measures in the robust design of a closed-loop supply chain, considering demand uncertainty of final products. In light of the advances in the reprocessing of goods to improve financial performance, the analysis of a closed-loop supply chain becomes crucial for the competitiveness of companies. We propose a multi-period model to solve the supply chain design problem in which several items must be produced through different levels after the production process, considering the flow of reverse of some products, which can be reprocessed or discarded. In this paper, we studied the design of a supply chain that includes several plants, distribution centers, collection centers, demand zones, and products; it consists of both products forward and reverses in the supply chain. Indeed, the perturbation parameters, robustness requirements, and the performance characteristics were identified qualitatively and quantitatively by determining their impact on the formulation and methodology. A variety of configurations are produced in the closed-loop supply chain, considering the variations of the uncertainty of the demand as a perturbation parameter. The objective is to maximize the economic value-added (EVA™); therefore, the most robust configuration is identified through robustness- EVA™ characterization and used to design the closed-loop chain. Finally, we present a numerical example using real information of the electronics industry in Bogotá to test the applied methodology and show that it is suitable for this type of problems.

1. Introduction

The Supply Chain Network Design (SCND) is an infrastructure problem in the management of the chain that involves strategic and tactic decisions [1,2]. It refers to the determination of the optimum number of facilities and their configuration, technology, quantities of purchases, production, distribution, inventories, and shipments between established facilities, in such a way as to guarantee customer satisfaction and increase the value of the chain [3]. In the design of any supply chain, the balance of customer service through the incorporation of suppliers, manufacturers, and distributors must be taken into account among other elements, which translate into physical elements such as facilities, factories, means of transport, warehouses, among others [4]. In the design of the supply chain, the ability of the organizations included in the supply chain to compete in the market must be determined, so a company that is trying to compete in a market with low costs will have difficulties if it includes high-cost suppliers in its supply chain.

Based on those above, it is understood that the design decisions are complex due to the multiple underlying variables in each level. These variables must also take into account a vision of future needs and alternatives that will drive various options in the best way to develop a flexible, cost-effective and service-oriented system [5]. The design of a supply chain network must reflect its best configuration through a variety of metrics that shows the best operation of all the elements included in the study [6]. According to this, many of the decisions in the supply chain involve complex interactions between opposing objectives [7].

Each process and the decision in the supply chains are predisposed to uncertainty. Thus, performing erroneous evaluations and judgments can lead to unforeseen events, which can have significant consequences when they are detected untimely. Accordingly, the uncertainty must be studied from the design phase of the chain [1].

The design of a supply chain can be efficient if it responds to interruptions, but this is a complex and significantly difficult task [8].

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https://doi.org/10.1016/j.omega.2018.09.003
0305-0483/

Thus those interested in the design of the supply chain strive to make their results efficient and competitive, but sensitive to risks and interruptions. The study developed by Wang et al. [9] demonstrated how investing in supply chain capabilities increases the company's ability to be more resistant and sensitive to disruptions. However, there is a gap in the literature on the balance between the increase in investment in supply chain capacities and the reduction of chain risks.

In the management of the supply chain, authors such as [10–13] have felt the need to analyze the risk that these uncertainties produce. Due to the complexity and interrelation of supply chains and the nature of uncertain events, the impact of any action has become a difficult or even impossible task to predict [14].

The inclusion of risk management in SCND problems has been addressed in the literature, although in quite limited contexts. In their review of supply chain risks, Tang and Nurmaya Musa [15] stated that there is still a lack of quantitative models for risk management in the supply chain since most of the literature is based on qualitative approaches.

Over the past decade, researchers have focused on the risks of the supply chain and the impact of these risks on supply chain design decisions. Thus Blackhurst et al. [16] studied the risks to the design of the product and the design of the manufacturing processes; the work proposed by Pishvaee and Razmi [17] integrated into their design variables of environmental risks to minimize the operating costs of the designed chain. Work [18] analysed the risks associated with supply and demand of products in the supply chain. On the other hand, Tsao and Lu [19] integrated into their design a model of discounts in transport costs as a source of risk. Finally, [20] designed a supply chain with the design of products as a visible source of risk in the capacity of suppliers and the demand for products.

However, SCND also faces uncertainties and risks from the economic environment. In every supply chain, there are financial flows as well as flows of physical products [1]. Financial operations supplement the physical flow of products and guarantee the financing of logistics operations Escobar [1] and Ramezani et al. [21]. This way, the resources generated become the core of any supply chain [22]. Therefore, the availability of financial resources in the design of the network should not be neglected to avoid the financial failure of a supply chain, guaranteeing from its projection not only the security of the flow of physical elements but also of financial flows [12]. Thus, the successful development and survival of organizations belonging to a supply chain depend on the role of financial management as well as the chain itself.

With those above, there are numerous challenges and implicit opportunities in the formulation, analysis, and calculation of the supply chain network design solutions under financial analysis. However, to date, there have been few developed models for this problem, leaving a large gap in the supply chain literature. Our endeavour to carry out a supply chain design under the analysis of Economic Value Added (EVA^{TM}) tries to express the true economic benefit of the entire chain faithfully. EVA^{TM} represents the most advanced instrument for measuring business performance based on the principle of value management [23]. The reason for this is a relatively simple approach compared to other evaluation criteria, also the possibility of complex application of this indicator in the management system for a supply chain.

In this context and based on the experience of the manufacturing sector, where the focus has been the evaluation of the added economic value of the supply chain; it is necessary to develop a methodology for the robust design of the supply chains in conditions of uncertainty by considering the Economic Value Added analysis. This paper proposes a method to solve this problem analyzing different configurations for a supply chain to choose one that preserves specific desired characteristics of the whole system despite the variations in demand, and that generates valuable knowledge for decision-making process for mass consumer products companies. The proposed methodology aims to answer two research questions: i) How to design a robust closed-loop supply chain under conditions of uncertainty that integrate financial criteria?, ii) How to introduce tactical and strategic decisions interconnected in a modeling approach to address the design of the closed-loop supply chain?

To solve both questions, this paper proposed a MINLP that integrates the financial risk evaluation of a closed-loop supply chain considering variability of de demand of final products. The mathematical model has been tested with real data obtained from a Colombian company of electronic products, seeking the robust design of the supply chain. The model considers multi echelons, multi products and multi periods, considering the reverse flow of some items. The main contribution of this paper is the mathematical structure of the proposed model, which considers a linearization of the objective function in order to obtain the maximum economic value-added (EVA^{TM}). Also, the paper identifies a methodology to obtain the perturbation parameters, robustness requirements, and the performance characteristics by considering strategic-tactical problems that support the use of aggregate information for certain aspects to be considered: the design of the closed-loop supply chains, the generation of Economic Value Added for a supply chain, the design of a metric of robustness for a closed-loop supply chain, and the use of financial indicators as robustness requirements and their impact on the methodology. In addition, the paper extends the literature of mathematical modelling applied to the closed-loop supply chain under uncertainty of the demand as a perturbation parameter.

This paper presents a literature review that supports the design of the mathematical model and the methodology used for the study. Then, the methodology shows the mathematical model and the formulation used to carry out the robustness analysis in the supply chain design. Also, we present a case study of a closed-loop supply chain for the development of electronics in the city of Bogotá, in which different suppliers, demand points, assembly plants and product recovery are studied. Finally, we present the conclusions and recommendations reached after the development of the research.

2. Literature review

This paper benefits from related articles to determine the importance of designing a robust closed-loop supply chain that includes financial reasons and whose objective is the maximization of the generation of value.

2.1. SCM models considering financial factors

According to Zhong et al. [24] classic supply chain models overlook the impact of financial factors on the overall performance of the supply chain. In practice, however, it has been shown that financial flow, as one of the three main flows, significantly affects the operational decisions of the supply chain [25].

In the relevant literature on the field, there are several examples of the application of different risk measures in the financial area, but few studies have been published in the area of supply chain design. We started analyzing the work of Comelli et al. [26] who built a multi-period deterministic mathematical model for the batch chemical process industry that combined programming and planning with the cash flow and budget management. On the same line, Badell et al. [27] proposed a multi-parameter, multi-disciplinary, deterministic model with Mixed Integer Linear Programming (MILP) for the batch process industries that integrate advanced planning and the programming at plant level considering cash flow and capital budget. The work proposed by Comelli et al. [28] combined master planning of the supply chain with the calculation of activity-based costs for the aggregate processes of the supply chain. In addition, Bertel et al. [29] maximized the average cash position in their decision model for operational planning of the supply chain based on a flow planning formulation. On the other hand, Hahn and Kuhn [30] developed a deterministic decision framework to optimize the Economic Value Added (EVA ^{TM}) as a performance metric based on the medium-term value of sales and operations planning.

A multi-objective stochastic programming model for a supply chain design under conditions of uncertainty is proposed in [31]; costs, demand, supply, processing, transport, shortage and expansion of capacity are considered as uncertain parameters but with the objective of minimizing costs and the probability of not meeting a certain budget. Also, Cardoso et al. [32] proposed a MILP formulation that integrates measures of financial risk in the design and planning of closed-loop supply chains (CLSC), taking into account the uncertainty of the demand, their objective is to maximize the Net Present Value (NPV) of the supply chain. In Paksoy and Bektaş [33], a mathematical model considering the trade off between several costs associated to environmental aspects and transportation of products for a closed-loop supply chain is proposed. The same authors in [34] describe a non-linear mathematical model considering strategic and tactical decisions for a closed-loop chain. The objective function minimizes the sum of the costs of transportation, suppliers, and of the costs of the reverse logistic. Finally, a fuzzy mathematical model is proposed for a CSCL by Özceylan and Paksoy [35]. Computational results validate the efficiency of the proposed approach showing applicability and flexibility.

A Mixed Integer Non-Linear Programming model by integrating financial performance with a credit solvency model for SCND decisions under economic uncertainty is formulated in [12]. The work introduced in [36] developed a multi-objective stochastic model for the design of the supply chain under conditions of uncertainty. The sources of risk are presented as a set of scenarios; the objective is to examine the advantages and disadvantages among the investments in improving the capacity of the supply chain and its risk reduction and to minimize its costs.

Finally, Longinidis and Georgiadis [37] proposed a mathematical model that integrates financial performance and the credit solvency model with SCND design decisions under economic uncertainty. The multi-objective programming model is MINLP and provides financial results through Economic Value Added (EVA ^{TM}) and credit rating through a valid credit-scoring model (Altman's Z score).

In this paper, we propose a MINLP mathematical model maximizing the Economic Added Value (EVA^{TM}). Unlike Longinidis and Georgiadis [37], we considered a closed-loop supply chain and sought to involve other financial evaluation indicators such as Net Present Value (NPV) and Weighted Average Cost of Capital (WACC) in addition to EVA^{TM}.

2.2. Robust chain design

When the design of the supply chain faces uncertainty, operational response policies must be adapted to cope with unforeseen events and the chain must be structured to be resistant to changes. According to Klibi et al. [38] since the financial flows are uncertain, the measures used to evaluate future actions of the supply chain network depend on the approach used to model the uncertainty. According to Vlajic et al. [39], one way of addressing financial uncertainty is by considering the concept of robustness. These authors also indicated that robustness could be regarded as both at the qualitative conceptual level and at the quantitative models level.

For Ali et al. [40] robustness is the preservation of certain desired characteristics of the system, despite fluctuations in the behaviour of its parts or the environment. According to Klibi et al. [41] the models considering uncertainty are usually solved by representative samples of possible future scenarios. In fact, the use of different scenario samples or different solution techniques leads to alternative designs. The designs suggested by the model must be compared with the status quo network. Whereon, none of the existing studies has integrated a methodology of financial difficulties modeling in the design of supply chains, structured to be resistant to changes. To fill this gap, this paper seeks to develop a robust design of supply chains under conditions of financial uncertainty. Incidentally, Ali et al. [40] proposed a methodology called FePIA Procedure (Features, Perturbation, Impact, Analysis), which is used as a robustness metric, that is, it quantitatively determines how robust a system is. The present work is based on the use of the methodology proposed by Tordecilla-Madera et al. [42], which in turn is based on that of Ali et al. [40]. We applied this methodology to the design problem of a closed-loop supply chain by adopting a MINL model. The achievement of this objective is what allows us to contribute to knowledge since no evidence of application of the FePIA procedure has been found in this context.

3. Methodology

The design of the closed-loop supply chain described in this article is based on the methodology proposed by Tordecilla-Madera et al. [42,43]. These authors introduced a general method based on a theoretical model to characterize the relationship between robustness and capacity planning cost and the warehouse location problem in supply chains. In their methodology, Tordecilla-Madera et al. [43] proposed four stages, which were meticulously applied in this work to the specific problem of a closed-loop supply chain.

In addition, we have considered the scenario generation technique based on historical data, where it is assumed that the historical behaviour of the demand dictates its future [48]. The number of scenarios can vary depending on the parameters with uncertainty that is desired for inclusion in the model.

3.1. Model description

In this section, we describe the business environment used to formulate the MINLP developed for the robust design of a closed-loop supply chain. We take into account several periods, one single product, and a multi-scale close loop network integrated by different suppliers, production facilities and distribution centers of forward and collection flow, as well as disposal centers to discard products that cannot be recovered in the reverse flow and marketplaces for the marketing of products. The type of logistics network studies thoughtfully the hybridization of the center of distribution, so it can integrate distribution and collection of products as production facilities do when they reprocess recovered products.

The development of the mathematical model emerged from the design of a network for the supply chain. In the beginning, this was made up by "i" suppliers, who will supply "j" production facilities. These production facilities have a special feature since they own the capacity to receive a product returned from the marketplaces as a result of guarantee processes, flaws in the product, reconditioning; all these characteristics in addition to the fabrication of a specific product. This idea arises from a new approach considered by Hatefi and Jolai [44], in which is important to bear in mind the design of reverse logistic networks when creating the supply chain to meet legal requirements in addition to environmental protection

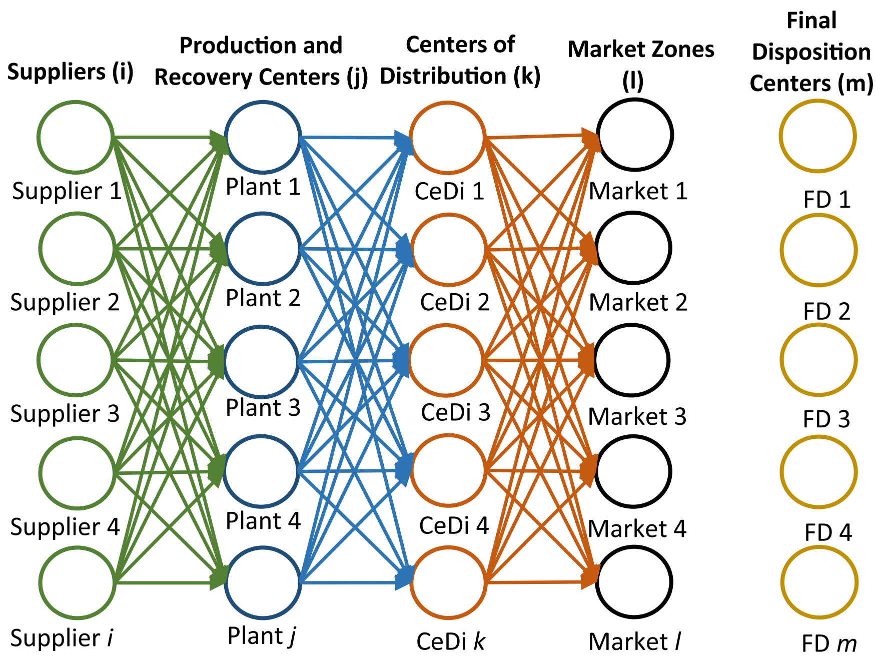


Fig. 1. Proposed network (Forward).

requirements. These latter ones are on the rise and, on the other hand, reflect economic benefits.

Another key element taken into account in the development of the network for the supply chain of this project is grounded in those risks that may affect its performance. According to Hatefi and Jolai [44] there are two big risk categories that we should consider when designing a supply chain. The first risk is caused by those difficulties resulted of a lack of coordination between demand and supply, and the second risk is generated by the interruption of normal activities, including situations out of control, such as natural disasters, economic distress, among others. Based on those above, we regarded demand variation as a perturbation parameter in the design of the supply chain of this project, since in real life demand has variations out of our control. Such variations involve risk can be caused by lack of coordination between demand and supply or due to the interruption in the performance of normal activities. For this reason, we did not delve into the definition of one perturbation parameter for each type of risk, since the demand can vary for one risk or another. However, we do not exclude the possibility of defining multiple perturbation parameters according to the investigation purpose and its depth; this could strengthen the chain when considering more risks that could be handled.

Once providers supply the facilities, the product is elaborated and sent to the “k” distribution centers available, which in their turn send the product to the “l” demand-driven market as it is illustrated in Fig. 1. After the product has been delivered to the “l” demand-driven market, it is possible to have returned as a consequence of guarantee processes, flaws in products or their reconditioning. This all considering the reverse logistics responsible for getting the items returned to the plant which will try, according to its capacity and the condition of the item, to recover it for its new incorporation into the system. The transport of the product starts from the market area to the distribution center and then from the distribution center to the production and recovery center, as shown in Fig. 2.

As soon as the recovery center processes the items and performs the respective treatment, the products return to the distribution center. Then the distribution center will evaluate which products can be sent to the corresponding markets or if they should be sent to the “m” available disposal areas when it is not possible to recover the product which will then be treated properly for its final disposal, as we illustrate in Fig. 3.

3.2. Characteristics and assumptions

The proposed model considers the following assumptions:

- All chain physical infrastructures are assumed to be within a single country, without the consideration of exportation of products or international physical distribution.
- The model considers the flow of network forward and reverse considering strategic and tactical decisions.
- The model includes as decision variables the opening and/or closure of recovery plants, distribution centers and disposal centers as well as the product flow forward and reverse through the chain. A distribution process that involves several multiproduct echelons is considered.
- Capacity and storage constraints both forward and reverse are considered for each echelon. It is assumed that all echelons can receive any finished product.
- The model does not consider limitations for the transportation mode.
- Deterministic demand values are used as fixed for the model. Also, a minimum and a maximum value of demand are considered for each market at each period. The demand must be satisfied for each customer.
- The only mode of transport considered is land transport (transport mode selection decisions are not included), and the truck-type selection decisions are not included. The variability of the response times has been included as a constant factor for the entire product flow in a determined route.
- The model explicitly takes into account financial considerations relative to taxes and tax benefits typical of commercialization processes.
- All the considered costs are deterministic and known a priori.
- The precedence relations of the flow of products are known.

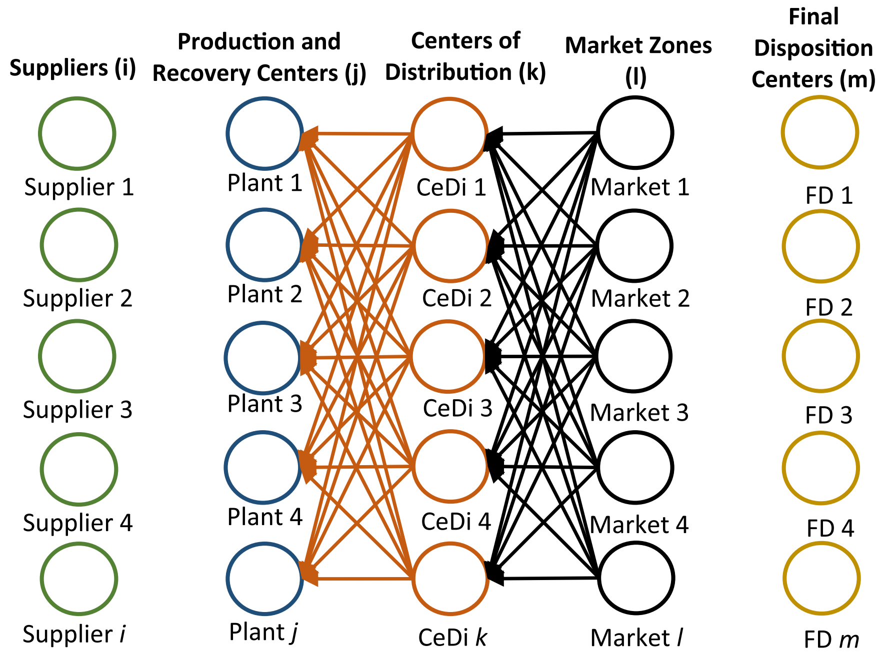


Fig. 2. Proposed network (Reverse).

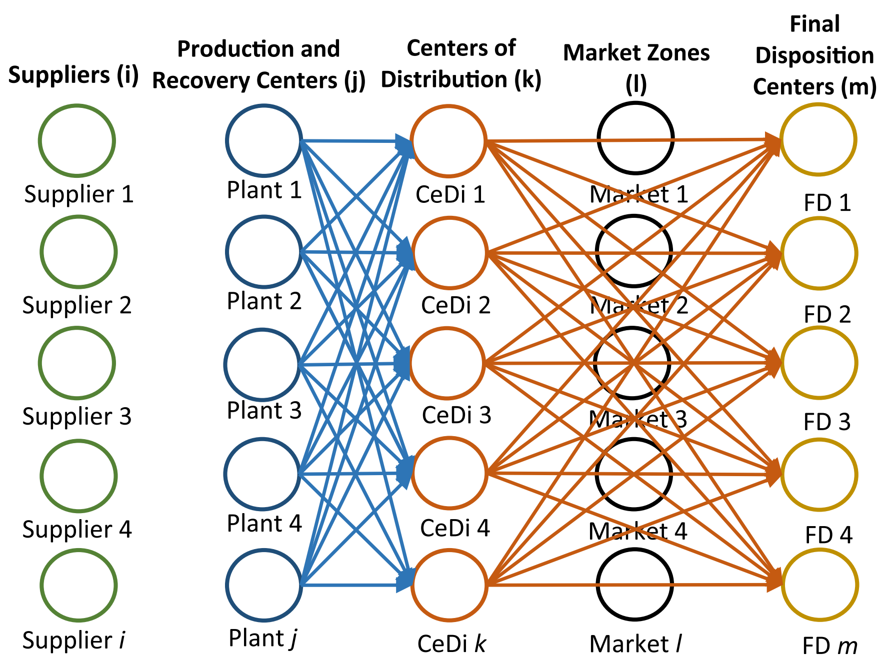


Fig. 3. Proposed network (Recovery).

The problematic is of substantial interest due to the opening of facilities forces companies to seek design or redesign strategies for their supply chain based on optimization tools to maintain high competitiveness. In this paper, the model considers decisions regarding the number of production and recovery plants, distribution centers and disposal centers to be opened, which give rise to the following questions: should a new facility be opened or closed? Where would the facilities convenient to open? Should there be one plant or several plants around a given country? Should we expand (open facilities) or contract (close facilities)? Is possible to find an optimal configuration of a supply chain optimal considering the robustness to changes in the demand and generating value for a company?

Therefore, there is a need to develop generic models to solve real problems that are related to the design of closed cycle supply chains, generating value for all their stakeholders. This aspect is the primary purpose of the proposed work in which a generic model is intended to inform those responsible for making decisions that manage supply chains. Therefore, the objective function of the proposed model is the maximization of the Economic Value Added EVA^{TM} [46]. The model is flexible and could be extended to closed-loop chains with similar characteristics.

The following indices, parameters and variables were defined in order to create the mathematical model:

Indexes

i: Number of suppliers; $i = 1, 2, \ldots, I$

j: Number of production and recovery centers; $j = 1, 2, \ldots, J$
k: Number of distribution and collection centers; $k = 1, 2, \ldots, K$
m: Number of disposal centers; $m = 1, 2, \ldots, M$.
l: Number of marketing areas; $l = 1, 2, \ldots, L$
t: Number of periods of time; $t = 1, 2, \ldots, NT$

Parameters
PD: Coefficient of variation of demand (0–100)
$dmin_{lt}$: Possible minimum value of demand for market l in period t
$dmax_{lt}$: Possible maximum value of demand for market l in period t
dem_{lt}: Value of demand for market l in period t
ret_{lt}: Return rate of used products in the marketing area l in period t
cp_j: Capacity of production and recovery center j
cpr_j: Capacity of production and recovery center j in reverse
dc_k: Capacity of distribution and collection center k
dcr_k: Capacity of distribution and collection center k in reverse
ce_m: Capacity of product disposition of disposal centers m
$inip_j$: Facility Initial investment j
$inicdr_k$: Initial investment of distribution center k
$inicd_m$: Initial investment of disposal center m
f_{jt}: Fixed cost of operation in production and recovery centers j in period t
g_{kt}: Fixed cost of operation in distribution and collection centers k in period t
h_{mt}: Fixed cost of operation in the disposal center m in period t
a_{jkt}: Cost of transport per unit from production and recovery center j to distribution and collection centers k, in period t
b_{klt}: Cost of transport and holding per unit from distribution and collection center k to marketing areas l in period t
e_{kjt}: Cost of transport and holding per recovered unit from the distribution and collection k to the production center j in period t
o_{kmt}: Cost of transport per discarded unit from the distribution center k to the disposal center m in period t
cr_{lkt}: Cost of transport per returned unit from the marketing area l to the distribution center k in period t
α_{jt}: Cost of production per unit in the production and recovery center j in period t
ρ_{it}: Purchase cost of material from supplier i in period t
η_{kt}: Cost for collection of used products in the distribution center k in period t
γ_{mt}: Cost for product discard in the disposal center m in period t
φ_{lt}: Penalty Cost for marketing area l in period t
pv_{lt}: Selling Price in marketing area l in period t
λ_{kt}: Cost of distribution of recovered products in the distribution center k in period t
Ad: Average loss rate
ir: interest rate
TR: Tax rate
ur: Retained profit percentage
vs: Salvage value
uc: Rate of subscription propagation
$CANA$: Capital provided with nominal value of already existing shares.
VAM: Equity value in the market
$TICP$: Interest rate in the short term
$TILP$: Interest rate in the long term
$TIRIE$: risk rate
TIR: Estimated return rate
$Co\beta$: Beta coefficient of the chain

Continuous and integer variables
X_{jkt}: Products sent from production and recovery facilities j to the distribution center k in period t
Y_{klt}: Products sent from distribution centers k to marketing areas l in period t
δ_{lt}: Unmet demand in marketing area l in period t
V_{lt}: Products selling in the marketing place l in period t
R_{lkt}: Products recovered from the marketing place l, sent to the distribution centers k in period t
RP_{kjt}: Products to be reprocessed taken from the distribution centers k to the production and recovery facilities j in period t
PR_{jkt}: Amount of recovered product taken from production and recovery facilities j and sent to distribution centers k in period t
W_{kmt}: Discarded Products sent from the distribution centers k to the disposal centers m in period t
P_{ijt}: Products obtained from the supplier i for production and recovery facility j in period t
$GARET_t$: Retained earnings in period t
$CPPLP_t$: Long-term accounts payable in period t
$CPPCP_t$: Short-term accounts payable in period t
CI_t: Invested Capital in period t
$GARET_t$: Retained earnings in period t
NEA_t: New Offering of shares in period t
$NAFI_t$: New shares for investments purposes in period t
$NCPPL_t$: New long-term accounts payable in period t
$NCPPC_t$: New short-term accounts payable in period t
CUP_{jt} Used capacity production of plant j in period t
$CUPR_{jt}$ Used capacity of recovery plant j in period t
$CUCD_{kt}$ Used capacity of distribution center k in period t
$CUCDR_{kt}$ Used capacity of recovery for distribution center k in period t
$CUCDS_{mt}$ Used capacity for disposal center m in period t

BINARY VARIABLES
Q_j: Opening or non-opening of production and recovery plant j
TCD_k: Opening or non-opening of distribution center k
U_m: Opening or non-opening of the disposal center m

4. Objective function

The objective function of the proposed approach is to maximize the Economic Value Added EVA™ [46], a widely used index that provides investors with an impartial evaluation since it overcomes the pessimistic interpretations of the net income reported in the company's income statement [45]. The calculation is made by subtracting the weighted average cost of capital (WACC), to the net profit after taxes shown in the statement of income. The WACC expresses, in general, the real costs associated with the main sources of capital used by the company (1). The value of *EVA* is calculated as follow:

$$EVA = \sum_{t=1}^{NT} BN_t - \sum_{t=1}^{NT} WACC_t * CI_t \quad (1)$$

Eq. (2) calculates the net operating profit after tax (BN_t) by subtracting short-term interest and long-term interest.

$$BN_t = GR_t - TICP * CPPCP_t - TILP * CPPLP_t \quad \forall t = 1, 2, \ldots, NT \quad (2)$$

On the other hand, we wanted to calculate the net profit for each evaluated configuration and for period t (GR_t), which is calculated by subtracting the cash inflows and outflows. In the model, we calculated it as illustrated in Eq. (3)

$$GR_t = (1-ir)\Bigg[\sum_{j=1}^{J} pv_{lt}V_{lt} - \sum_{j=1}^{J}\sum_{k=1}^{K}\left(\alpha_{jt}+a_{jkt}\right)X_{jkt} - \sum_{k=1}^{K}\sum_{l=1}^{L}(\rho_{kt}+b_{klt})Y_{klt} - \sum_{l=1}^{L}\sum_{k=1}^{K}(\eta_{kt}+cr_{lkt})R_{lkt} - \sum_{k=1}^{K}\sum_{j=1}^{J}\left(\lambda_{kt}+e_{kjt}\right)RP_{kjt} - \sum_{m=1}^{M}\sum_{k=1}^{K}(\gamma_{mt}+o_{kmt})W_{kmt} - \sum_{j=1}^{J}\sum_{k=1}^{K}\left(a_{jkt}PR_{jkt}\right) - \sum_{l=1}^{L}\varphi_{lt}\delta_{lt} - \sum_{i=1}^{I}\sum_{j=1}^{J}\rho_{it}P_{ijt}\Bigg] + (ir*DP_t)\ \forall t = 1,2,\ldots,NT \quad (3)$$

Constraints (4)–(6) formulate the general balance for the supply chain. We started with the basic equation of balance, where the left side is equal to the right side. That is, the total assets must be equal to the assets of the investors plus the total liabilities as shown in constraint (4).

$$AF_t + EFEC_t + CPC_t = CAAPOR_t + GR_t + CPPLP_t + CPPCP_t \quad \forall t = 1,2,\ldots,NT \quad (4)$$

Total assets (AT_t) are the result of the addition of fixed assets, cash and accounts receivable as shown in the following constraint (5).

$$AT_t = AF_t + EFEC_t + CPC_t \quad \forall t = 1,2,\ldots,NT \quad (5)$$

Fixed assets (AF_t), according to constraint (6), are the result of the addition of existing and new assets.

$$AF_t = EXIST_t + RECIENT_t \quad \forall t = 1,2,\ldots,NT \quad (6)$$

By accounting principles, the cost of acquiring fixed assets should not tax the fiscal period in which this acquisition occurred, but all tax periods (estimated useful life of the asset) that benefit from its use. Depreciation is the allocation of the cost of fixed assets to the fiscal periods that benefit from their use as a means to equate expenses with revenues. As if this enormous cost was attributed to a single fiscal period, the profitability information will be misleading. Constraint (7) show the calculation of the depreciation (DP_t) for each period t.

$$DP_t = \frac{(1-vs)FCI_t}{NT} \qquad \forall t = 1,2,\ldots,NT \quad (7)$$

Constraint (8) defines that existing fixed assets are calculated as existing fixed assets of the previous period minus depreciation. When expressing the new fixed assets, a distinction is necessary between the initial period or creation of the chain and the following periods. Therefore, it is necessary to establish the amount of the initial assets before the planning of the supply chain ($EXIST_t$).

$$EXIST_t = EXIST_{t-1} + RECIENT_t \quad \forall t = 1,2,\ldots,NT \quad (8)$$

Constraint (9) shows the calculation of the new assets ($RECIENT_t$). It indicates that its initial value is zero.

$$RECIENT_t = FCI_t - DP_t * FCI_t \quad \forall t = 1,2,\ldots,NT \quad (9)$$

The fixed capital invested (FCI_t) in each period is calculated in constraint (10), as the cost of opening plants, distribution centers and disposal centers.

$$FCI_t = \sum_{j=1}^{J}(f_{jt}*Q_J) + \sum_{k=1}^{K}(g_{kt}*TDC_k) + \sum_{m=1}^{M}(h_{mt}*\ U_m) \quad \forall t = 1,2,..,NT \quad (10)$$

Constraint (11) defines current assets as the sum of liquid assets, such as cash and accounts receivable. Cash is defined ($EFEC_t$) in constraint (12) as the cash of the previous period plus a percentage of addition to the retained earnings.

$$AC_t = EFEC_t + CPC_t \quad \forall t = 1,2,..,NT \quad (11)$$

$$EFEC_t = EFEC_{t-1} + ur*GARET_t + (1-uc)*NEA_t \ \ \forall t = 1,2,..,NT \quad (12)$$

Accounts receivable (CPC_t), the other component of current assets is defined in constraint (13) as the accounts receivable of the previous period plus the remaining percentage of addition to the accumulated earnings.

$$CPC_t = CPC_{t-1} + (1-ur)*GARET_t \quad \forall t = 1,2,..,NT \quad (13)$$

Constraint (14) defines the total invested capital as shareholders equity (CI_t), short-term liabilities, and long-term liabilities. Assets (PAT_t), as shown in constraint (15), described as the sum of the contributed capital and the retained earnings. In constraint (16), the added capital ($CAAPOR_t$) is defined as the contributed capital from the previous period plus the new offering of shares obtained from the capital markets. Constraint (17) establishes the new shares issued for working capital investment purposes.

$$CI_t = PAT_t + CPPLP_t + CPPCP_t \quad \forall t = 1,2,..,NT \quad (14)$$

$$PAT_t = CAAPOR_t + GR_t \quad \forall t = 1,2,..,NT \quad (15)$$

$$CAAPOR_t = CAAPOR_{t-1} + NEA_t \quad \forall t = 1,2,..,NT \quad (16)$$

$$NEA_t = NAFI_t \quad \forall t = 1,2,..,NT \quad (17)$$

Constraint (18) define the accumulated earnings as the retained earnings of the previous period plus the addition to the retained earnings. The liability ($Rtotal_t$) is the sum of the short-term liabilities and the long-term liabilities, as shown in constraint (19). The short-term liabilities are defined in constraint (20) as short-term liabilities of the previous period plus new short-term liabilities of the financial cycle for the supply chain. Similarly, long-term liabilities are defined in (21) as the long-term liability of the previous period plus the new long-term liabilities of the financial cycle of the current fiscal year.

$$GR_t = GR_{t-1} + GARET_t \quad \forall t = 1,2,..,NT \quad (18)$$

$$Rtotal_t = CPPLP_t + CPPCP_t \quad \forall t = 1,2,..,NT \quad (19)$$

$$CPPCP_t = CPPCP_{t-1} + \ NCPPC_t \quad \forall t = 1,2,..,NT \quad (20)$$

$$CPPLP_t = CPPLP_{t-1} + NCPPL_t \quad \forall t = 1,2,..,NT \quad (21)$$

Working capital (CW_t) is defined as current asset minus liabilities in the short term (22). The number of outstanding shares (NAC_t) is determined by constraint (23) by dividing the contributed capital with the nominal value of the shares. The market value of the equity ($VACC_t$) is the number of outstanding shares and the market value of the shares, shown in constraint (24). Finally, the total installation cost of the distribution and disposal centers and plants should be financed through a combination of new offerings with fixed capital investment purposes and new long-term accounts payable, due to the configuration of the supply chain. Constraint (25) presents the net value of earned cash to pay the fixed asset installation cost by multiplying the term with the addition of the new offerings with fixed capital investment purposes.

$$CW_t = AC_t - CPPCP_t \quad \forall t = 1, 2, .., NT \tag{22}$$

$$NAC_t = AC_t / CANA \quad \forall t = 1, 2, .., NT \tag{23}$$

$$VACC_t = NAC_t * VAM \quad \forall t = 1, 2, .., NT \tag{24}$$

$$FCI_t = (1 - uc) * NAFI_t + NCPPL_t \quad \forall t = 1, 2, .., NT \tag{25}$$

Constraint (26) shows the calculation of the $WACC_t$, a figure that expresses the cost of capital for the company and shows the required performance of the assets of the company [37]. Since the supply chain uses debts and social capital to pay for its operations, the total cost of capital is a combination of the necessary earnings to pay returns to its creditors and shareholders. The Capital Accounts Payable Model (CAPM) is used as no model shows directly the return investors should receive. CAPM determines the expected profitability of a particular asset and has three terms [37]. The first term is the risk-free interest rate. It is the return for a risk-free investment. The second term, the difference between the expected return of the market, is the reward for the investment of capital in the market. It, therefore, has an average systematic risk. The third term, the beta coefficient, is the amount of systematic risk of a particular asset and relative to the risk of an average asset. On the contrary, the cost of the debt can be observed directly since it is the interest rate that the company pays for the new loans. Since a company has both short-term debt and long-term debt with an appropriate weight, based on the portion of each type of debt within its total debt, it is necessary to weight the short and long-term liabilities in the calculation of the WACC.

$$WACC_t = \Big[\big(\tfrac{PAT_t}{CI_t} (TIRIE + (TIR - TIRIE) Co\beta \big) + \Big(\tfrac{CPPCP_t + CPPLP_t}{CI_t} \Big(\tfrac{CPPCP_t}{Rtotal_t} TICP + \tfrac{CPPLP_t}{Rtotal_t} TILP \Big) (1 - TR) \Big) \Big] \quad \forall t = 1, 2, .., NT \tag{26}$$

Note that part of the objective function is non-linear due to product of $WACC_t$ plus CI_t. Thus, it is necessary to perform a linearization of the objective function associated with this part of the objective function. In particular, we considered the value of weighted average cost of capital in period t ($WACC_t$) as a fixed parameter according to [47] for the entire supply chain. Therefore, we have considered a new variable D_t, defined as the cost of capital of the money invested of the supply chain at period t. Thus, $D_t = WACC_t * CI_t$ is defined. Therefore, the objective function (1) is reformulated by (27).

$$EVA = \sum_{t=1}^{NT} BN_t - \sum_{t=1}^{NT} D_t \tag{27}$$

In Constraint (28), the model is limited to the fact that the number of products sent to each market plus the unmet demand for products must equal the total demand. The quantity of sent products to each market plus the unmet product demand must be equal to the total demand.

$$\sum_{k=1}^{K} Y_{klt} + \delta_{lt} = dem_{lt} \quad \forall t = 1, 2, .., NT; l = 1, 2, .., L \tag{28}$$

The number of recovered products in market one is calculated, by considering the defined return rate per period multiplies the unmet demand minus the total demand and this valued. This calculation is illustrated in constraint (29).

$$\sum_{k=1}^{K} R_{lkt} = ret_{lt} * (dem_{lt} - \delta_{lt}) \quad \forall t = 1, 2, .., NT; l = 1, 2, .., L \tag{29}$$

In constraint (30), the addition of products sent from the plant to the distribution center and the products taken to be reprocessed from the distribution center to the plant must be equal to the number of products sent from the distribution center to the markets.

$$\sum_{j=1}^{J} X_{jkt} + \sum_{j=1}^{J} RP_{jkt} = \sum_{l=1}^{l} Y_{klt} \quad \forall t = 1, 2, .., NT; k = 1, 2, .., K \tag{30}$$

The quantity of disposed products from the distribution center to the disposal center equals the quantity of recovered products in market 1 multiplied by the average of losses. This calculation is shown in constraint (31).

$$\sum_{m=1}^{M} W_{kmt} = Ad * \sum_{l=1}^{L} R_{lkt} \quad \forall t = 1, 2, .., NT; k = 1, 2, .., K \tag{31}$$

Constraint (32) shows that products taken to be reprocessed from the distribution center to the plant must be equal to 1, minus the losses average rate multiplied by the quantity of returned products in market 1 to be reprocessed.

$$\sum_{j=1}^{J} RP_{kjt} = (1 - Ad) * \sum_{l=1}^{L} R_{lkt} \quad \forall t = 1, 2, .., NT; k = 1, 2, .., K \tag{32}$$

The number of products sent for reprocessing from the distribution center to the plant must be equal to the number of products for check up from the plant to the distribution center. This calculation is shown in constraint (33).

$$\sum_{k=1}^{K} RP_{kjt} = \sum_{k=1}^{K} PR_{jkt} \quad \forall t = 1, 2, .., NT; j = 1, 2, .., J \tag{33}$$

The quantity of sent products from the plant to the distribution center must be below or the same as the plant capacity. Its calculation is shown in constraint (34).

$$\sum_{k=1}^{K} X_{jkt} \le cp_j * Q_j \quad \forall t = 1, 2, .., NT; j = 1, 2, .., J \tag{34}$$

Constraint (35) calculates the amount of products taken to be reprocessed in the plant must be less than or equal to the capacity of the reverse plant.

$$\sum_{k=1}^{K} RP_{kjt} \le cpr_j * Q_j \quad \forall t = 1, 2, .., NT; j = 1, 2, .., J \tag{35}$$

The number of products sent from the distribution center to the markets must be less than or equal to the capacity of the distribution center. Its calculation is illustrated in constraint (36).

$$\sum_{l=1}^{L} Y_{klt} \le dc_k * TCD_k \quad \forall t = 1, 2, .., NT; k = 1, 2, .., K \tag{36}$$

The number of products recovered from the markets for reprocessing in the distribution center must be less than or equal to the collection capacity of the distribution center. Its calculation is shown in constraint (37).

$$\sum_{l=1}^{L} R_{lkt} \le dcr_k * TCD_k \quad \forall t = 1, 2, .., NT; k = 1, 2, .., K \tag{37}$$

Table 1
Minimum demand per period.

	Period 1	Period 2	Period 3	Period 4	Period 5
mar1	59	91	68	100	87
mar2	56	90	69	98	88
mar3	52	81	72	98	89
mar4	59	96	67	96	90
mar5	56	82	75	98	87
mar6	55	82	65	97	89
mar7	60	84	67	97	89

Table 2
Maximum demand per period.

	Period 1	Period 2	Period 3	Period 4	Period 5
mar1	164	124	144	123	139
mar2	164	123	148	123	157
mar3	170	128	147	121	152
mar4	164	129	148	126	138
mar5	165	123	142	123	159
mar6	172	124	143	129	169
mar7	161	126	145	121	148

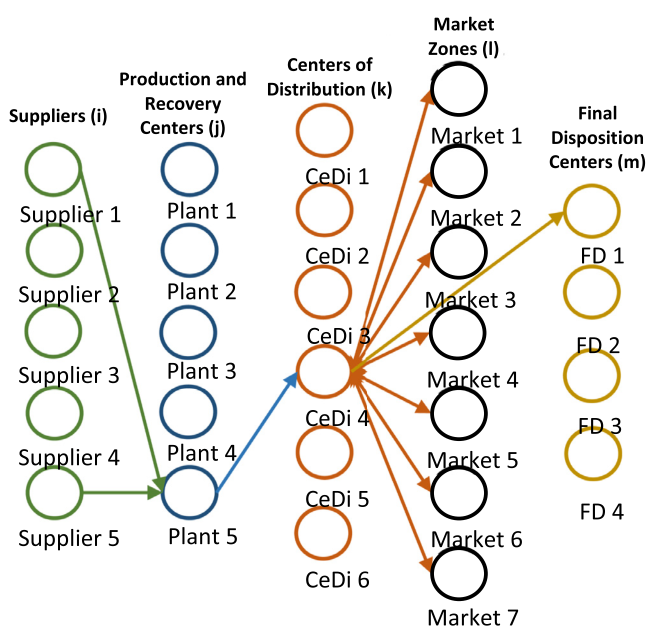


Fig. 4. Configuration 1.

In Constraint (38), the quantity of products sent to the disposal center must be less than or equal to the capacity of the disposal center.

$$\sum_{k=1}^{K} W_{kmt} \leq ce_m * U_m \quad \forall t = 1, 2, .., NT; m = 1, 2, .., M \tag{38}$$

The quantity of bought products from the supplier must be equal to the quantity of products to send to the distribution center. Its calculation is shown in constraint (39).

$$\sum_{i=1}^{I} P_{ijt} = \sum_{k=1}^{K} X_{jkt} \quad \forall t = 1, 2, .., NT; j = 1, 2, .., J \tag{39}$$

The quantity of sent products from the distribution center to the markets must be equal to the amount of sold products in the market. Constraint (40) shows this calculation.

$$\sum_{k=1}^{K} Y_{klt} = V_{lt} \quad \forall t = 1, 2, .., NT; l = 1, 2, .., L \tag{40}$$

Table 3
Obtaining configurations first run.

Scenario	Demand (Unit/year)	Variation *PD* (%)	Total Initial Investment (COP $)	NPV (COP $)	IRR	Suppliers (#)	Plants (#)	Distribution Center (#)	Disposal Center (#)	% Unmet Demand
π1	2787	0	−220,000,000	47,150,072	29%	1.5	5	4	1	1%
π2	2897	5	−220,000,000	63,615,138	32%	1.5	5	4	1	2%
π3	3007	10	−220,000,000	70,606,511	34%	1.5	5	4	1	2%
π4	3117	15	−220,000,000	78,888,916	36%	1.5	5	4	1	3%
π5	3226	20	−220,000,000	91,793,593	36%	1.5	2,4	4	1	0%
π6	3336	25	−220,000,000	100,624,428	38%	1.5	2,4	4	1	1%
π7	3446	30	−220,000,000	107,630,389	40%	1.5	2,4	4	1	2%
π8	3556	35	−220,000,000	116,601,350	43%	1.5	2,4	4	1	3%
π9	3666	40	−220,000,000	123,622,714	44%	1.5	2,4	4	1	4%
π10	3776	45	−220,000,000	132,946,406	42%	1.5	1,5	3,4	1	0%
π11	3886	50	−220,000,000	145,267,817	45%	1.5	1,5	3,4	1	1%
π12	3995	55	−220,000,000	155,132,073	47%	1.5	1,5	3,4	1	2%
π13	4105	60	−220,000,000	157,475,620	45%	1.5	2,5	3,4	1	0%
π14	4215	65	−220,000,000	164,085,106	46%	1.5	2,5	1,4	1	1%
π15	4325	70	−220,000,000	154,070,878	44%	1.5	2,5	1,4	1	2%
π16	4435	75	−220,000,000	164,571,704	44%	1.5	3	2,4	1	0%
π17	4545	80	−220,000,000	163,030,990	44%	1.5	3	2,4	1	1%
π18	4654	85	−220,000,000	166,856,054	43%	1.5	1,2,5	4,5	1	0%
π19	4764	90	−220,000,000	167,971,854	43%	1.5	1,2,5	4,5	1	1%
π20	4874	95	−220,000,000	168,906,833	43%	1.5	1,2,5	4,5	1	1%
π21	4984	100	−220,000,000	160,530,574	41%	1.5	1,2,5	4,5	1	2%

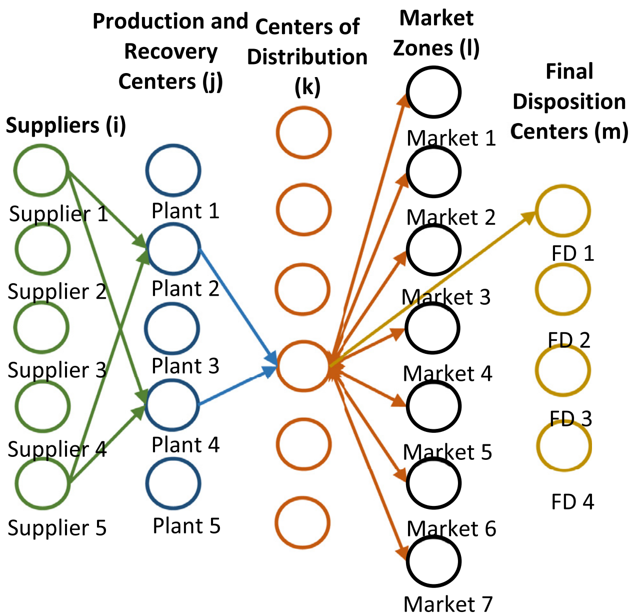


Fig. 5. Configuration 2.

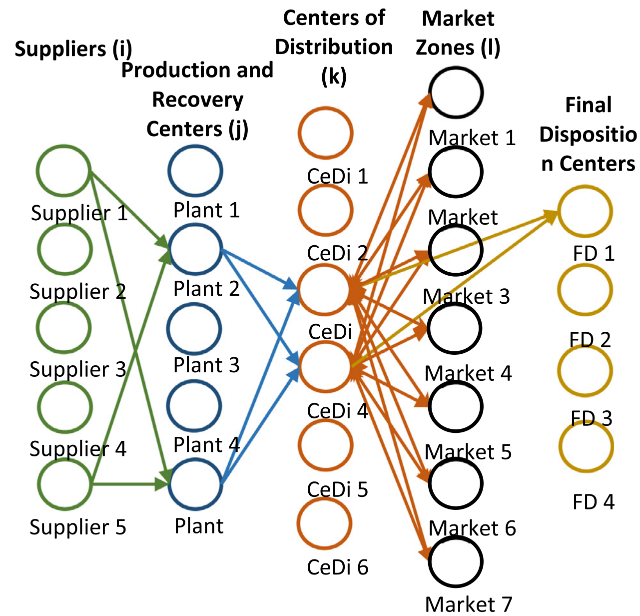


Fig. 7. Configuration 4.

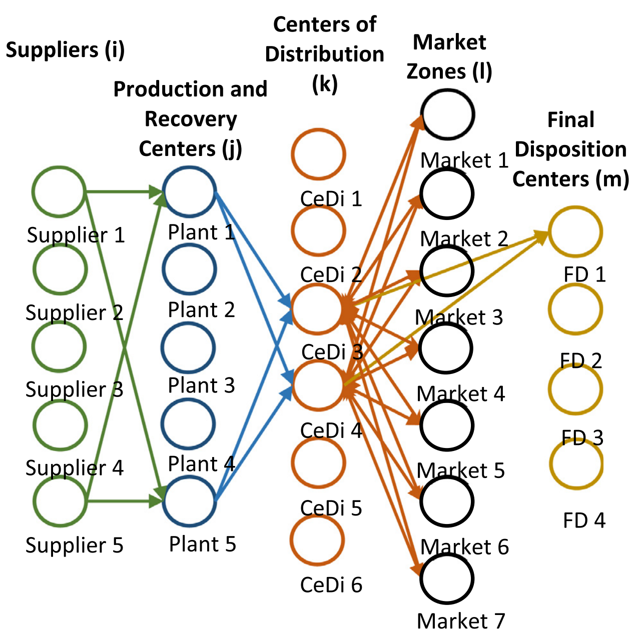


Fig. 6. Configuration 3.

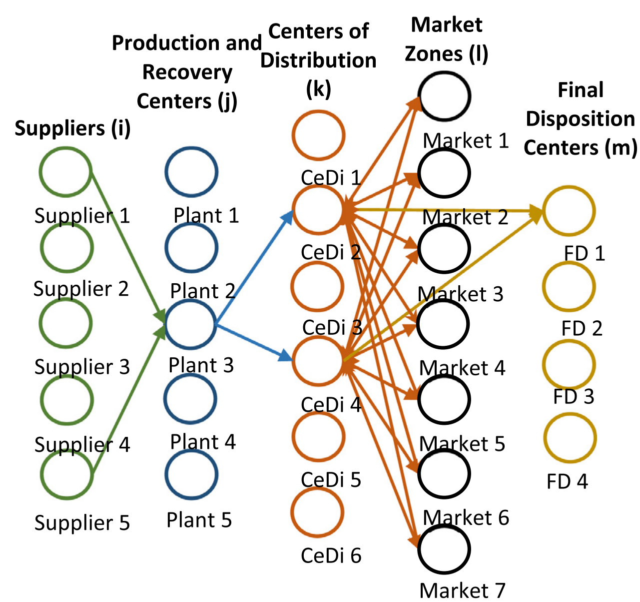


Fig. 8. Configuration 5.

Total initial investment is calculated in constraint (41) and corresponds to the addition of the initial value assumed by each open plant, distribution center and disposal center.

$$FCI_t = \sum_{J=1}^{J} (inip_j * Q_J) + \sum_{k=1}^{K} (inicdr_k * TDC_k) + \sum_{m=1}^{M} (inicd_m * U_m) \quad \forall t = 1, 2, .., NT \tag{41}$$

Constraints (42)–(46) correspond to the calculations to evaluate the used capacity in plants, distribution and disposal centers.

$$CUP_{jt} = \sum_{k=1}^{K} X_{jkt}/cp_j \quad \forall t = 1, 2, .., NT;\ j = 1, 2, .., J \tag{42}$$

$$CUPR_{jt} = \sum_{k=1}^{K} PR_{jkt}/cpr_j \quad \forall t = 1, 2, .., NT;\ j = 1, 2, .., J \tag{43}$$

$$CUCD_{kt} = \sum_{l=1}^{L} Y_{klt}/dc_k \quad \forall t = 1, 2, .., NT;\ k = 1, 2, .., K \tag{44}$$

$$CUCDR_{kt} = \sum_{j=1}^{J} RP_{kjt}/dcr_k \quad \forall t = 1, 2, .., NT;\ k = 1, 2, .., K \tag{45}$$

$$CUCDS_{mt} = \sum_{k=1}^{K} W_{kmt}/ce_m \quad \forall t = 1, 2, .., NT;\ m = 1, 2, .., M \tag{46}$$

$$Q, TCD, U \in \{0, 1\}$$

Appendix 1 shows the values of the parameters used for this research.

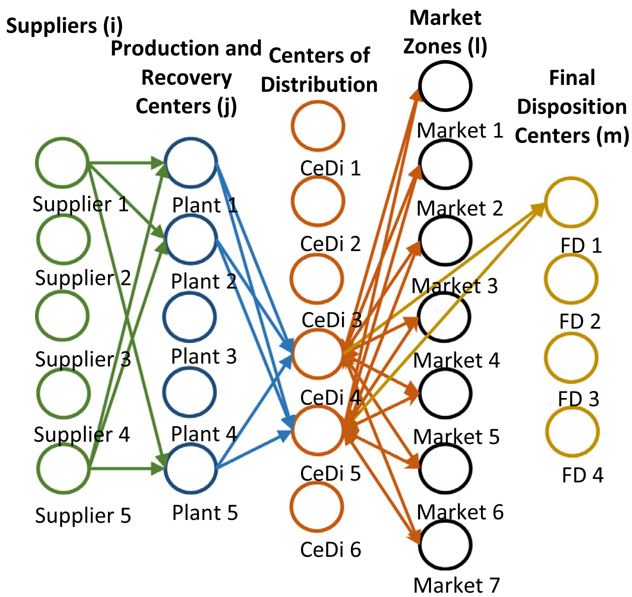


Fig. 9. Configuration 6.

4.1. FePIA methodology

The main objective of this research is to design a model for value creation in a supply chain. The FePIA procedure was used for the robustness metric proposed by Ali et al. [40], and supported by the works of Tordecilla-Madera et al. [42,43]. This methodology can be defined as a series of steps that will provide a way to measure the robustness of any system considering the resources of its system, operating characteristics and the effects of the defined disturbance parameters.

The FePIA methodology suggests a series of steps, which will be explained hereunder. The robustness requirement (Γ) must be selected, which, through a quantitative and qualitative measurement, will allow establishing whether the studied system is robust or not. Once the robustness requirement is defined, the performance characteristics of the system must be determined (Φ), which will have quantitative variations that may or may not be allowed according to the maximum and minimum values $\langle \beta_J^{min}, \beta_J^{max} \rangle$ that are defined and that will allow compliance with the requirement of robustness. Then, it will be necessary to determine the perturbation parameters (Π), which will affect the robustness requirement and the established performance characteristics, and it is usually environmental disturbances such as variations in demand among other factors.

For the design of the supply chain of this project, the demand has been selected as a parameter of disturbance (Π), because this may vary due to internal and external factors such as the behavior of the economy, competition, among others. The design of the network for the proposed supply chain operates for five periods (years) in which each will have a defined demand per market (dem_{lt}); the demand varies between a maximum ($dmax_{lt}$) and minimum ($dmin_{lt}$) values established in Tables 1 and 2 respectively.

The variability of the demand has described a set of discrete scenarios considering the minimum and maximum values of demand found in Tables 1 and 2 and following Eq. (47). This equation is composed of a coefficient of variation (PD) varying from 0% to 100% in 5% intervals, resulting in 21 scenarios (π) of demand.

$$dem_{lt} = dmin_{lt} + (dmax_{lt} - dmin_{lt}) * \left(\frac{1}{PD}\right) \qquad \forall\, l, t \tag{47}$$

Once the three previous steps have been completed, we will analyse the effect of this variation on the operation characteristics (Φ) through experimentation and intentional controlled variation of the perturbance parameter (Π). Finally, we will review the effect of the intentional controlled variation of the perturbation parameter on the established robustness requirement.

4.2. Selection of the financial requirement of robustness

The robustness requirement can be defined as the measure or the response on which it will be evaluated whether the system is robust or not. The disturbance parameter will affect the robustness requirement positively or negatively due to the controlled variation. The variation will generate different alternatives of use of available resources as well as all the possibilities in the configuration of distribution networks and their associated costs among other resources that can be managed. Even when there may be disturbances the objective will be to satisfy the established requirement and maximize the performance of the system and its profitability. This will lead the system to be more robust when the resources aforementioned are optimized and will give the system the capacity to operate under sub-optimal conditions but will guarantee desired operating characteristics.

Since the formulation of this project, we highlighted the interest of using financial indicators to evaluate the robustness of the supply chain to be designed. As the first requirement of robustness (Γ_1) we determined the IRR. This calculation is of great importance since it directly indicates the rate of return of the project. This indicator facilitates the decision-making regarding deciding on what project to invest when you have multiple options. One should not forget that its calculation is effective only in projects with equal economic lives according to Rodado et al. [46]. On the other hand, based on the literature review carried out on multiple indicators, it was possible to show that there is a relationship between the IRR, the WACC, the MARR (Minimum Acceptable Rate of Return), and the NPV, since the calculation of one approximates the calculation of the other. As a result, factor two evaluated the relationship and highly valued these indicators.

Additionally, the IRR is a complete indicator, and since its value is higher than the WACC, it can be guaranteed that the investment made will be covered and yields will be generated. Another advantage is that in its calculation the real rate of return of the project will be found by analyzing income and expenditures. Additionally, it considers all cash flows and their distribution over time [46].

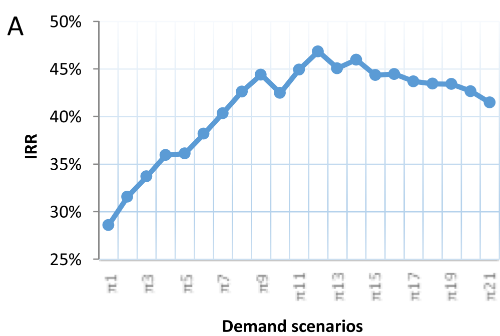
To select the IRR as a robustness requirement, it is necessary to define the minimum value to evaluate the robustness of the supply chain design. For the calculation of this value, it is necessary to determine the $WACC_0$, which allows identifying which is the associated cost for whatever the source of financing, whether they are banks, investors, among others. For the calculation of the $WACC_0$ it is needed to first determine the cost of the debt: The cost of the debt for this paper is calculated in Eq. (48) below:

$$Cost\ Debt = i(1 - Tax\ Rate) \tag{48}$$

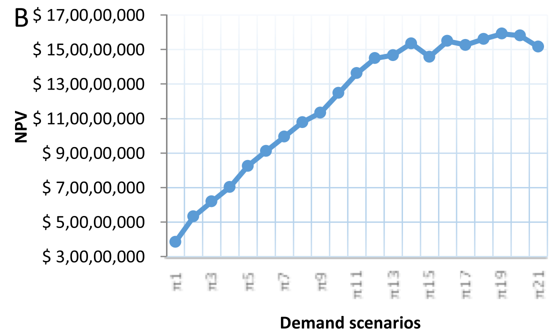
$i = Loan\ Rate\ A.\ E$

5. Case study

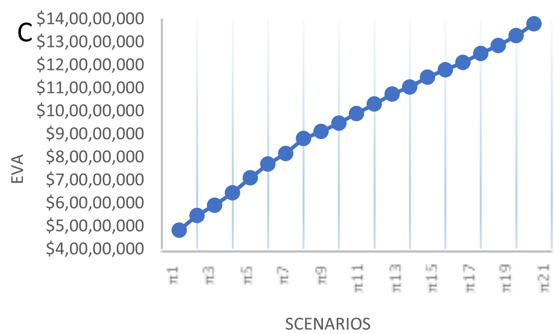
The application of the proposed mathematical model for the robust design of a supply chain is illustrated through a real-world case study for a company that will assemble an electronic product in the city of Bogotá. For reasons of confidentiality, the company will be referred to as the Company. This company is conducting a strategic planning process for the next five years. Currently, it is evaluating the structure of the network to select the optimal configuration that gives the Company an advantage regarding satisfaction of the demand and in the creation of value for the shareholders. The Company has evaluated the possibility of installing five assembly plants of the electronic product in different areas of Bogotá,



IRR for each initial scenario



NPV for each initial scenario



EVA for each initial scenario

Graph 1. Behaviour of the robustness requirement and the objective function.

and also has determined to have a contract with four possible disposal centers of the ECOLECTA network and centers of distribution, a dangerous waste management programme by the district secretary of the environment of Bogotá, who will be in charge of giving final disposal to the electronic waste that cannot be recovered in recycling stages. Market research has determined the creation of seven zones for the sale of the electronic product in Bogotá and its surroundings, said zones would remain in the planning period. Therefore, the calculations of dividends, retained earnings, assets, liabilities, patrimony, costs of shipping products from suppliers, to marketing, collection and disposal centers are from just one company. The supply network of the company fits into Figs. 1– 3.

6. Results

The design of the supply network for the *Company* is based on the mathematical model (1)–(45). The model is solved using MINLP. The solution of the model was coded in GAMS® Software Version 22.5 by using Solver CPLEX 12.1 in a computer with Intel® CORE ™ i5 processor; The model contains 21,737 variables, 96,741 restrictions and an average of 790 s of CPU usage with a maximum of 997 s of CPU usage. As we applied a linearization for the objective function, the solutions obtained with this solver are optimal.

Additionally, the robustness level of the system was analyzed considering Eq. (48), establishing different study scenarios associated with compliance with the demand. Thence, the variations to the disturbance parameter provided relevant information such as the amount sent from one node to another and the costs associated with said transfers. Additionally, they show the capacity used in plants, distribution centers, and disposal centers, as well as satisfied market demand. It also provides information on capital invested in each period and the cash flows per period, key values to calculate the robustness requirement (IRR), as well as relevant information on the Profit and Loss statement and Balance Sheet of the supply chain analyzed for the research.

6.1. Possible configurations

After the formulation of the mathematical model, we carried out the respective simulations in the GAMS® software, executing the variation of the perturbation parameter for 21 study scenarios. We did it to analyse the possible configurations (Table 3) of the designed network that will later be evaluated with the FePIA methodology.

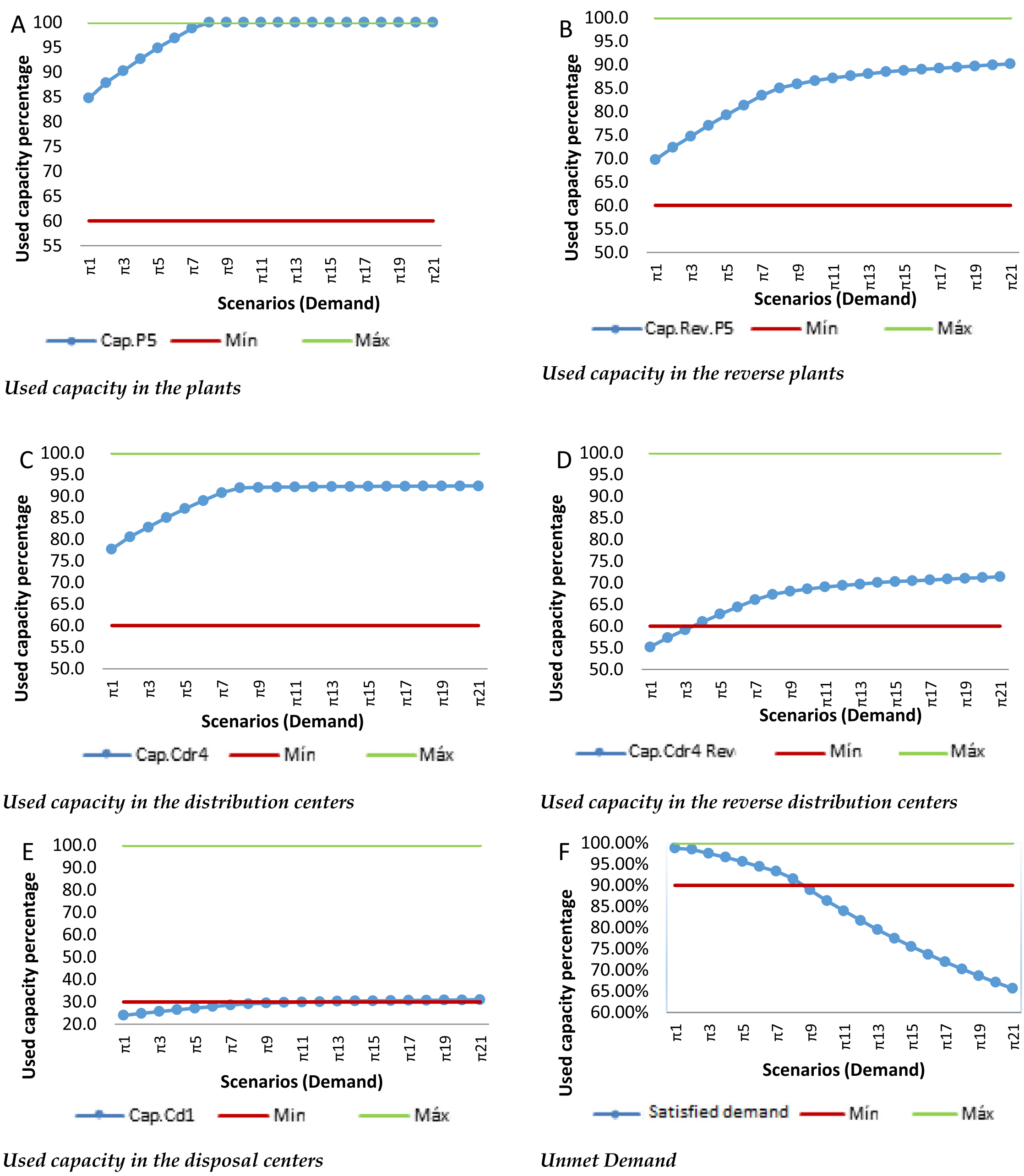
We obtained six configurations from Table 3, the results of the first simulation with the 21 defined scenarios, and without restrictions of the plants, distribution centers and disposal centers to be used. These configurations will be used to meet the demand and maximize the EVA™. These configurations will later be evaluated with the FePIA methodology to determine their level of robustness, such configurations can be observed highlighted with orange.

Graph 1 shows the changes presented in the robustness requirements and in the objective function, evidenced as the demands increase, the perturbation parameter, the IRR, NPV and EVA™ values increase.

These graphics indicate a direct relationship between demand levels, Net Present Value, Internal Rate of Return and Economic Added Value.

6.2. Analysis of scenarios and the effect of disturbance parameters on operating characteristics

Once the variations in the disturbance parameter were made to determine the different scenarios, we analyzed the used capacity of the plants, distribution centers, and disposal centers, as well as the percentage of satisfied demand. They were selected as operating characteristics of the system, for each of them.



Used capacity in the plants

Used capacity in the reverse plants

Used capacity in the distribution centers

Used capacity in the reverse distribution centers

Used capacity in the disposal centers

Unmet Demand

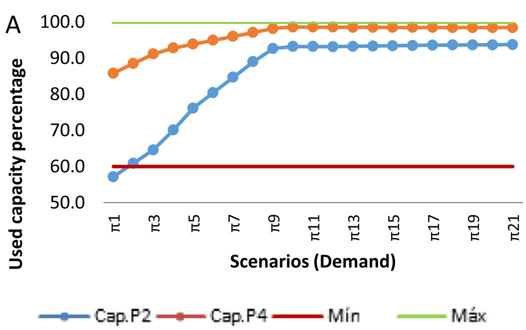
Graph 2. Behaviour of the variables in configuration 1.

6.2.1. Configuration 1

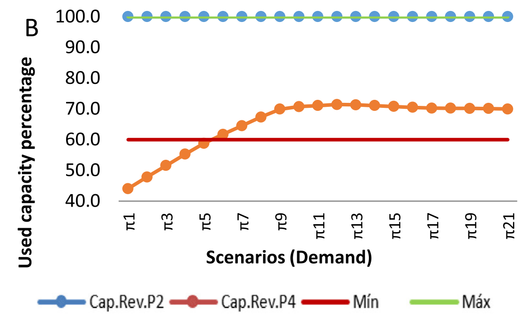
In this scenario, we propose the use of one of the five available plants. The fifth plant, which is in charge of manufacturing the product, and once the product is ready is sent to the fourth distribution center. This center is the only one enabled for this configuration out of the six distribution centers available. Finally, the products will be sent to the seven demand markets. The defective products that are generated and cannot be recovered will be sent to the disposal center 1, discarding the remaining three. This configuration is one of the two configurations in which only one plant is operated. Its representation corresponds to Fig. 4.

Graph 2-A shows that the capacity used of plant 5 in this configuration is above the minimum established. Therefore, in scenario $\pi 8$ where demand has increased, maximum use of 100% is reached, which generates unmet demand since it is the only plant in operation.

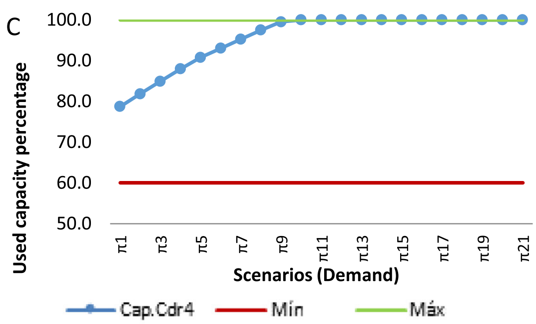
Graph 2-B shows that the used capacity to recover products from plant 5 is above the minimum established and does not present difficulties with overuse of capacity. In the case of the distribution center (Cdr), in this configuration the enabled center (Cdr4) makes use of its capacity higher than 60%, which is the defined minimum, this is observed in Graph 2-C. Also, there is no maximum use of capacity. Graph 2-D shows that the use of the capacity of Cdr4 in the collection of products from the markets for recovery is above the minimum 60% defined from the scenario $\pi 4$. When the demand is low capacity is not used as expected. In the case of the disposal centers (Cd) in Graph 2-E, the capacity used of the single open center (Cd1) is below the established minimum, and as demand increases, its use increases. Finally, in Graph 2-F, for configuration 1, the satisfied demand is above the established minimum of 90% up to an approximate demand of 37,758 units, from the scenario $\pi 10$. When the demand exceeds the capacity of the plant 5, a bottleneck is created that generates unmet demand.



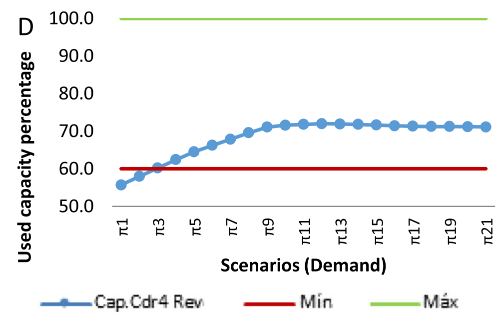
Used capacity in the plants - Configuration 2.



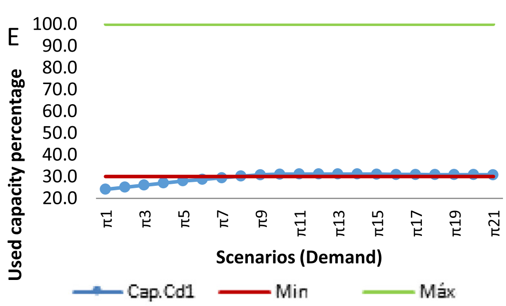
Used capacity used in reverse plants - Configuration 2.



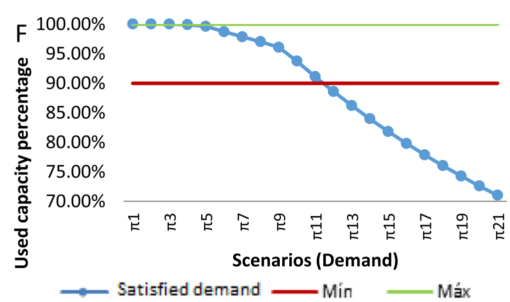
Used capacity in the distribution centers



Used capacity in the reverse distribution centers



Used capacity in the disposal centers



Unmet Demand

Graph 3. Behaviour of the variables in configuration 2.

6.2.2. Configuration 2

Configuration 2 proposes the use of 2 of the 5 available plants. These are plants 2 and 4, where plant 4 has greater capacity than plant 2. The distribution centers are operated only with the Cdr4 as well as configuration 1. Finally, disposal center Cd1 will continue to be used as in the previous configuration. Fig. 5 represents configuration 2.

According to Graph 3-A, for configuration 2, the use of plants 2 and 4 exceeds the minimum established capacity, from demand scenario $\pi 9$. Plants have a constant use greater than 90%, in scenarios of low demand underutilizes plant 2. This infringes, only in one scenario, the restriction of 60% minimum use of capacity.

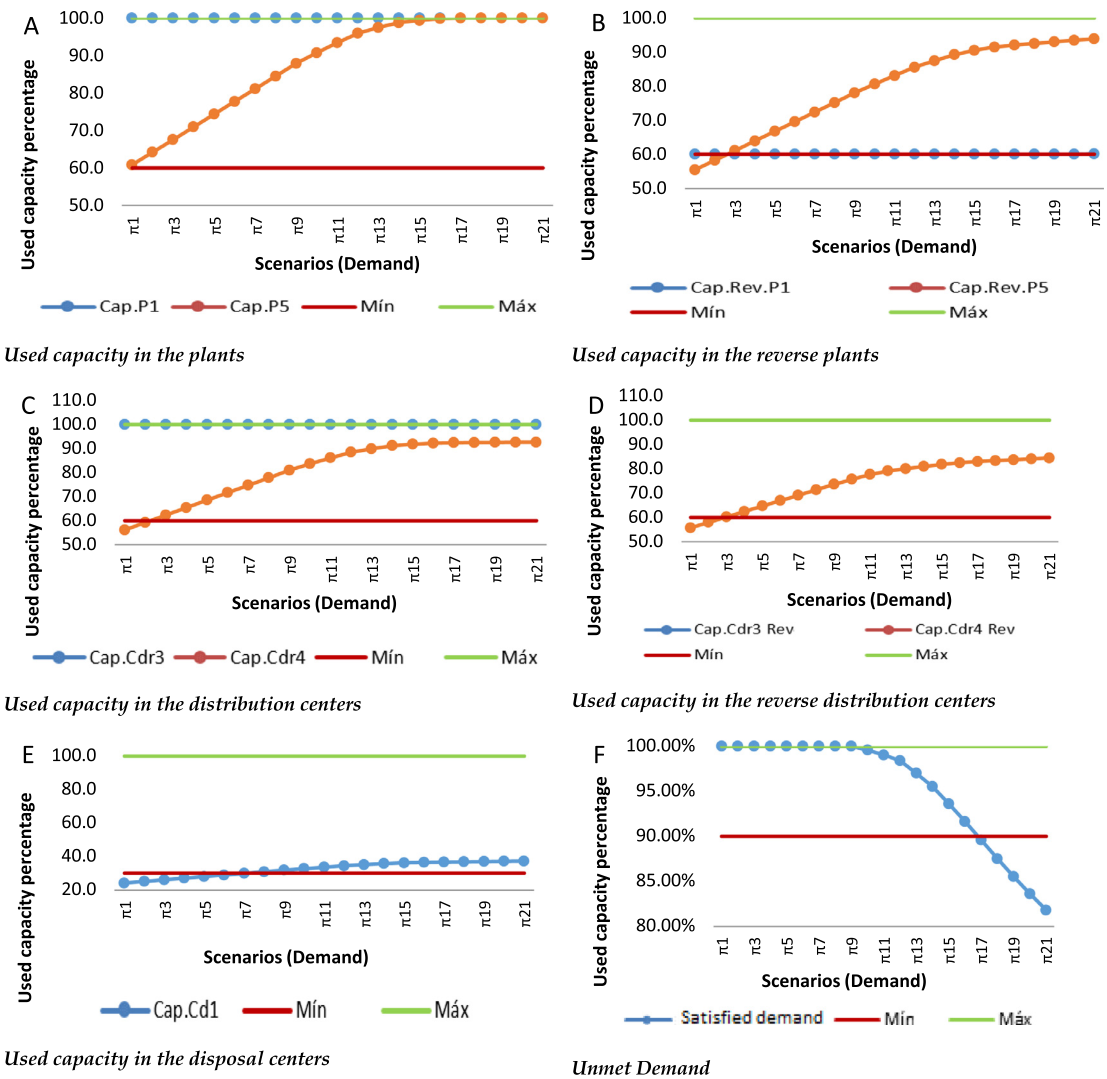
Regarding the recovery capacity of the plants in Graph 3-B, plant 5 operates at 100% and in complement, plant 4 assumes the recovery of products that plant five cannot assume. When the demand is less than 32,262 units, plant four will work with a capacity of less than 60%. Graph 3-C shows the capacity used in Cdr4 is above the defined minimum and reaches a 100% utilization with an estimated demand of 37,758 units, which will generate unmet demand for higher requirements. Graph 3-D shows the capacity for collection of products returned from Cdr4 exceeds the minimum established when the demand is greater than 30,064 units. In the case of the disposal centers (Graph 3-E), the capacity used in Cd1 has a behaviour similar to configuration one where the defined minimum is only exceeded as the demand increases. This may be demonstrating that the capacity defined for this installation is high for the rate of products that are discarded. Finally, Graph 3-F shows the satisfied demand of the configuration two is above the established minimum of 90%, in 11 of the 21 scenarios. When the demand exceeds 38,855 units approximately, Cdr4 cannot continue to send products since it reaches its maximum capacity.

6.2.3. Configuration 3

Configuration 3 proposes the use of 2 plants out of the 5 available. The plants used are number 1 and number 5, where plant 5 has 5 times more capacity than number 1. Distribution centers 3 and 4 are used, two out of the six available. Finally, the disposal center used continues to be number 1. Fig. 6 shows this configuration.

In Graph 4-A, we can observe the use of plants 1 and 5 in configuration 3 is above the established minimum, reaching the use of 100% of both plants in scenario 17, which may generate unmet demand.

Regarding the used capacity of the plants for recovery, in Graph 4-B, it is evident that for plant 1 the capacity used is above the minimum established in all scenarios with only 60%. For plant



Graph 4. Behaviour of the variables in configuration 3.

5 in 2 out of the 21 scenarios, the use of the plant is below the minimum. Graph 4-C shows that the capacity used in Cdr3 is 100% and as demand increases, Cdr4 supports the operation almost reaching 100% utilization in both Cdrs in periods of high demand. In the case of reverse distribution centers (Graph 4-D), it is observed that the capacity used in Cdr3 in the 21 scenarios is below the minimum. The opposite occurs with Cdr4, that uses above 60% of its capacity. As Cdr4 has a higher capacity assumes a higher percentage. In the case of the disposal centers according to Graph 4-E, the capacity used in Cd1 shows low utilization as it barely exceeds the minimum used capacity. For configuration 3, the demand is met in the first 17 possible scenarios, as shown in Graph 4-F. It becomes the configuration with less unmet demand until now, its limitation being the capacity of the plants.

6.2.4. Configuration 4

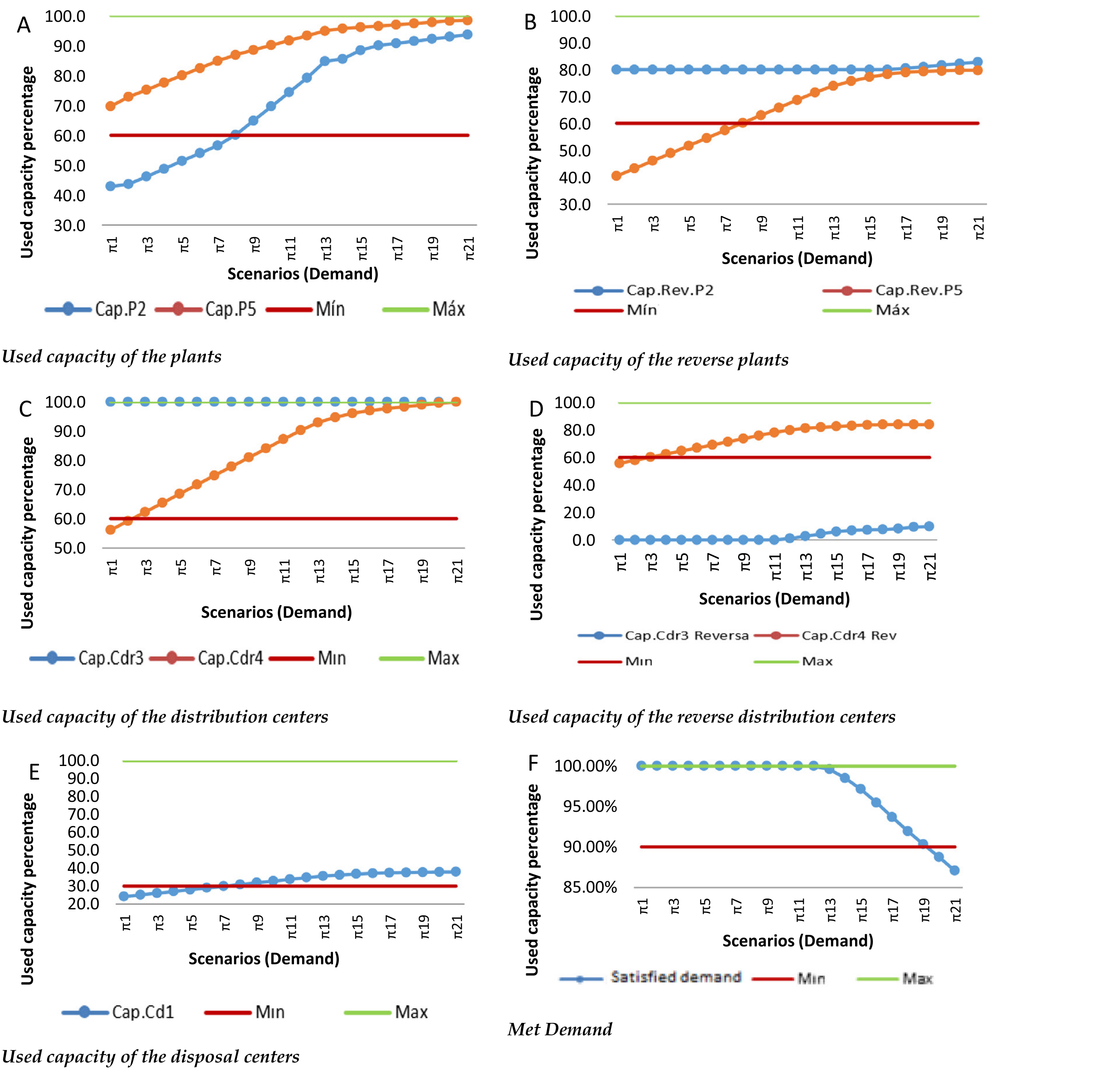
For this configuration, distribution centers 3 and 4 are used, the same as in configuration 3. The plants used in this case are numbers 2 and 5. Finally, the disposal center used is number 1. This configuration is represented in Fig. 7.

In Graph 5-A, we can observe that for configuration 4 the use of plant 5 is greater because it has greater capacity than plant 2. Plant 2 is below the minimum established capacity in 7 out of the scenarios when the demand is low.

Regarding the used capacity of the plants for recovery in Graph 5-B, it is evident that plant 2 operates at 80% of its capacity. It does not reach 100% because it leaves products to plant 5 to justify its operation since the installation has already been assumed. In the case of the distribution centers for configuration 4, we can observe that the used capacity of Cdr3 operates at 100% and Cdr4 supports the operation with greater capacity. Both Cdr exceed the minimum of operation from scenario 2, (Graph 5-C). The capacity of the reverse distribution centers, represented in Graph 5-D, exposes that the Cdr4 has greater used capacity compared to Cdr3. This because the cost of distribution is lower in Cdr4. In configuration 4, the disposal center 1 operates on the defined minimum capacity in 14 out of the 21 scenarios. It presents a similar behaviour to the configurations analysed so far, as shown in Graph 5-E. In configuration 4, the minimum satisfied demand of 90% is met in the first 19 possible demand scenarios, as shown in Graph 5-F, exceeding the 17 scenarios obtained in configuration 3.

6.2.5. Configuration 5

Configuration 5, shown in Fig. 8, is the second of the configurations that operates with a single plant as well as configuration 1. However, plant 3 that is used in configuration 5 is the plant with greater capacity and in turn with a higher initial investment cost. This configuration uses distribution centers Cdr2 and Cdr4. Finally, the disposal center used continues to be Cd1.



Graph 5. Behaviour of the variables in configuration 4.

In Graph 6-A, we can observe that for configuration 5 the use of plant 3 exceeds the minimum capacity of 60% established in 20 out of the total scenarios.

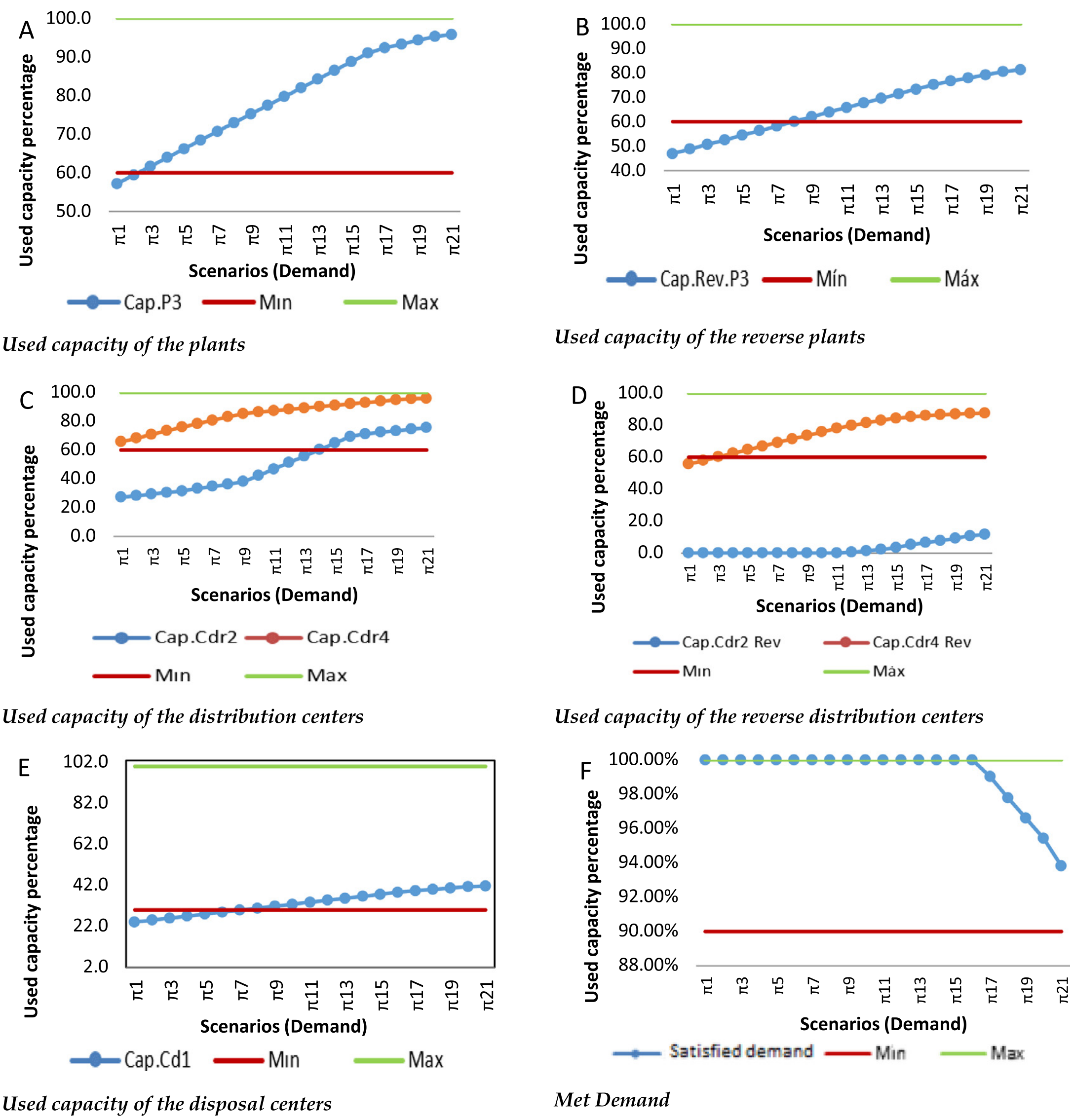
Regarding the used capacity for recovery of plant 3 (Graph 6-B), it is evidently above the minimum established capacity from scenario 8. This is because being the largest plant, it has greater capacity and in periods of low demand, capacity does not exceed 60%. In the case of the distribution centers for configuration 5, Graph 6-C shows that the used capacity of Cdr2 in 13 of the scenarios is below the minimum. In (Cdr4), on the contrary, the capacity is above the minimum established for the 21 scenarios. In the case of reverse distribution centers, it is evident that the used capacity in Cdr2 is below the minimum. This because the distribution cost is lower in Cdr4 (Graph 6-D). For configuration 5, disposal center 1 operates on the defined minimum capacity in 14 out of the 21 scenarios. It presents a behaviour similar to the configurations analysed up to now, as shown in Graph 6-E. For configuration 5, the minimum demand of 90% is met in the 21 possible scenarios, as can be seen in Graph 6-F. There are no bottlenecks for plants or distribution centers as in the configurations previously analysed. However, once the robustness requirements have been analysed, it will be possible to review if there is any effect on the cash flows when considering the plant with greater capacity and installation cost.

6.2.6. Configuration 6

Configuration 6 is the only configuration that works with 3 out of the 6 available plants. These plants are number 1, 2 and 5. This configuration operates with two distribution centers, which are Cdr4 and Cdr5. Finally, the disposal center used continues to be Cd1. This configuration is represented in Fig. 9.

In Graph 7-A we can observe that for configuration 6 the use of plant 1 reaches 100%. This because it is the smallest plant proposed. Plants 2 and 5 support the manufacture, however, the plant 2 works with a capacity of less than 60% in 16 of the lowest demand scenarios.

Regarding the used capacity of the plants for recovery in Graph 7-B, it is evident that plants 1 and 2 operate on the minimum established capacity in all scenarios. However, plant 5 only operates above the minimum capacity when the demand is greater than 41,053 units approximately (scenario $\pi 13$). Graph 7-C shows distribution centers in configuration 6. Here, the capacity used for



Graph 6. Behaviour of the variables in configuration 5.

Cdr5 is 100%, because the distribution cost is lower than that of Cdr4. Used capacity in Cdr4 is below the minimum in the first 11 scenarios where the demand is lower. In the case of reverse distribution centers, it is evident in Graph 7-D that the capacity used in Cdr4 in 17 of the scenarios exceeds the defined minimum. On the contrary, Cdr5 does not exceed 16% of utilization, this because the distribution cost is lower in Cdr4. In configuration 6, the disposal center 1 operates on the minimum defined capacity in 14 of the scenarios, presenting behaviour similar to all the configurations analysed (Graph 7-E). In configuration 6, as can be seen in Graph 7-F, the minimum demand of 90% is met in the 21 possible scenarios, as it has three plants in operation.

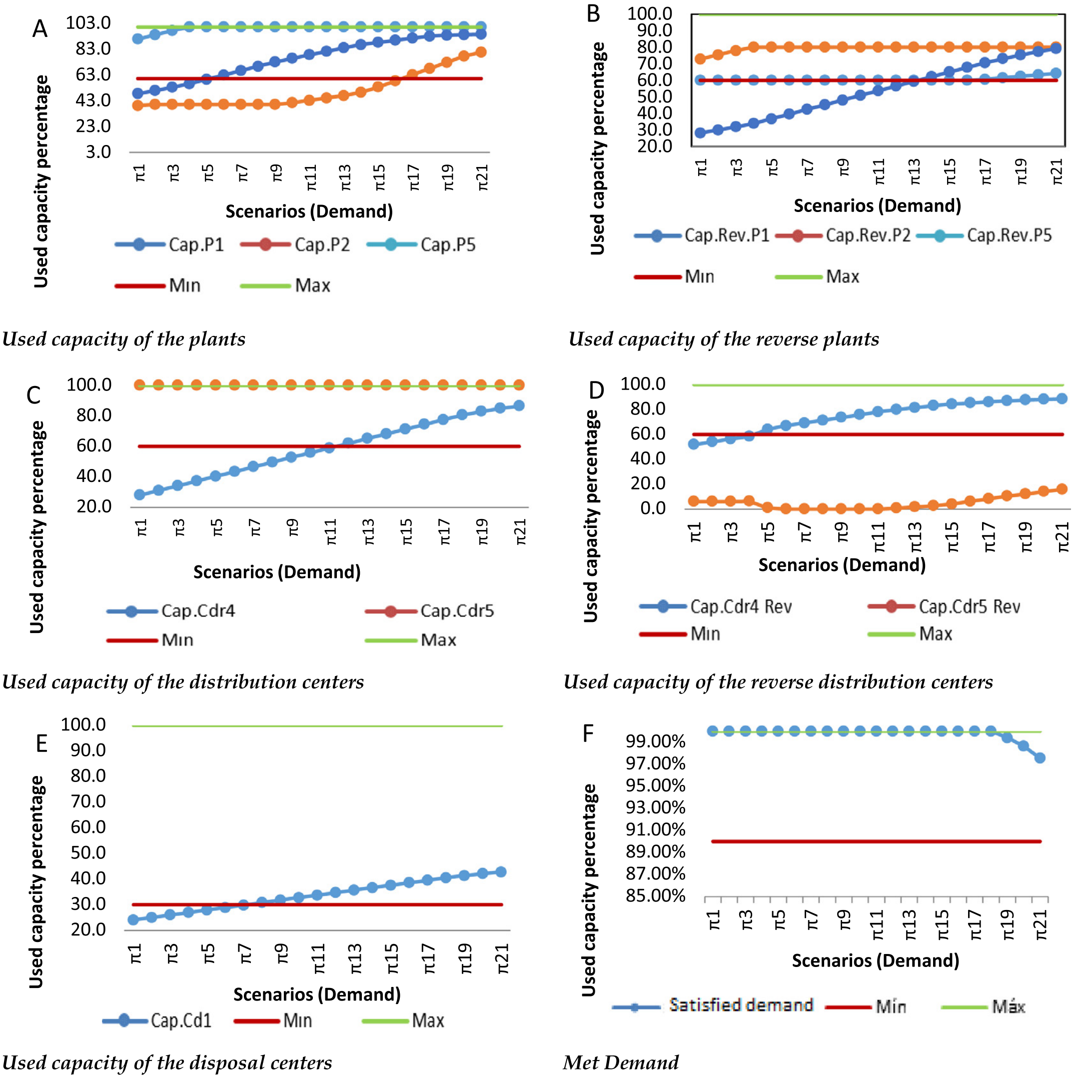
In summary, each configuration has advantages and disadvantages depending on the demand of the respective markets. Both will be reflected in the use of the capacity of the facilities, the level of satisfaction of the demand and the cash flows that will be studied in the analysis of the robustness requirement. For example, configuration 1 takes profit of the capacity of the plant and the distribution center over the minimum of 60%. However, the capacity of plant 5 only allows supplying the first 8 demand scenarios. When the demand increases above this value, 90% of satisfied demand mark cannot be met and penalization costs begin to be assumed. It is a suitable configuration for low demand scenarios. (It shows 8 scenarios in total of over 90% met demand).

Configuration 2 has behaviour somewhat similar to configuration 1. Demand is met by 90% in more scenarios, however, distribution center 4 reaches its maximum capacity with a demand of around 38,855 units. As the configuration is greater, it ceases to be ideal. (In total, 11 scenarios of met demand over 90%).

Configuration 3, unlike the previous 2 configurations, operates with 2 plants and 2 distribution centers, where the decision to use one installation more than another will depend on the cost of the operation in Cdr. In the one installation working at full capacity, the other will support the operation to reduce unmet demand. However, in this configuration there is still a bottleneck due to the capacity of the plants. If demand is higher than 45,449 units, the minimum met demand of 90% will no longer be fulfilled. (In total, 16 satisfied demand scenarios above 90%).

Configuration 4, like the previous configuration, operates with 2 plants and 2 distribution centers. The variations presented is the used capacity of the distribution centers and a higher number of scenarios in which demand is met above the 90% defined. (In total, 19 met demand scenarios above 90%).

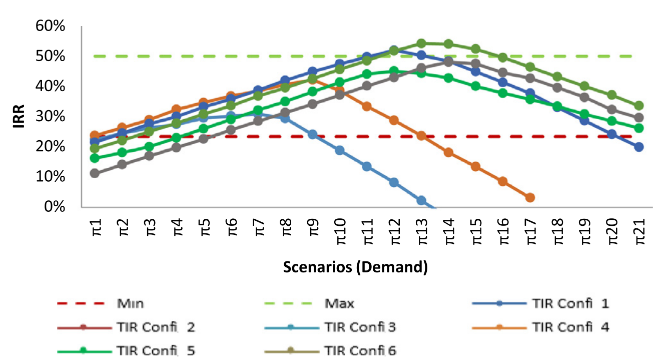
Configuration 5 proposes the use of only one plant and one distribution centers, being those of greater capacity and therefore



Graph 7. Behaviour of the variables in configuration 6.

higher initial value. Having the highest capacity, its percentage of utilization is reduced because the demand remains the same regardless of the configuration. Although, in all scenarios the minimum demand of 90% is met, the financial impact of this decision would have to be analysed. This is part of the analysis of the robustness requirement. (In total, 21 met demand scenarios above 90%).

Finally, configuration 6 proposes the use of 3 plants and 2 distribution centers. This allows the unmet demand to be reduced. However, from the graphic it is evident that some of the facilities have a used capacity below the defined minimum capacity. Such situation can generate losses since its installation cost is assumed, but its use is very low. (In total, 21 satisfied demand scenarios above 90%).



Graph 8. Effects of the perturbation parameter on the robustness requirement.

6.3. Determination of the effects of the perturbation parameter on the robustness requirement

The following steps proposed by the FePIA methodology include the determination of the effect of the variation of the perturbation parameters on the robustness requirements. In this case, it is the Internal Rate of Return (IRR) and Present Net Value (VPN) in order to determine the most robust configuration for the designed and proposed supply chain.

Graph 8 was made in order to analyse the IRR for each configuration in the 21 proposed scenarios.

The IRR, the robustness requirement, in this case, was calculated from the cash flows in each configuration and is evaluated concerning the minimum MARR calculated in Eq. (48). It corresponds to a MARR of 23.4%. This IRR value is the minimum acceptable rate in a scenario to consider the configuration as robust. According to Graph 8, configurations 1 and 2 have the highest IRR in the low demand scenarios. This as they can supply the de-

Table 4
Ideal configuration according to known demand.

Ideal configuration according to known demand		
Configuration	Ideal scenarios (π)	Met demand (Units) until:
Configuration 1	π1, π2, π3, π4, π5, π6	3336
Configuration 2	π7, π8, π9	3666
Configuration 3	π10, π11, π12, π13	4105
Configuration 4	π14, π15	4325
Configuration 5	π16, π17	4545
Configuration 6	π18, π19, π20, π21	4984

Table 5
Number of scenarios per configuration.

Number of scenarios per configuration that exceed the minimum IRR	
Configuration	N. of Scenarios
Configuration 1	7
Configuration 2	12
Configuration 3	19
Configuration 4	19
Configuration 5	17
Configuration 6	16

mand with their capacity even working with one plant in the case of configuration 1, or with one distribution center in the case of configuration 2. On the other hand, the other configurations have more facilities, which meant high investments, and affect the cash flows by reducing the IRR for those configurations. However, once configurations 1 and 2 reach their maximum capacity, they begin to have problems to meet the demand assuming penalty costs that generate a decrease in the IRR.

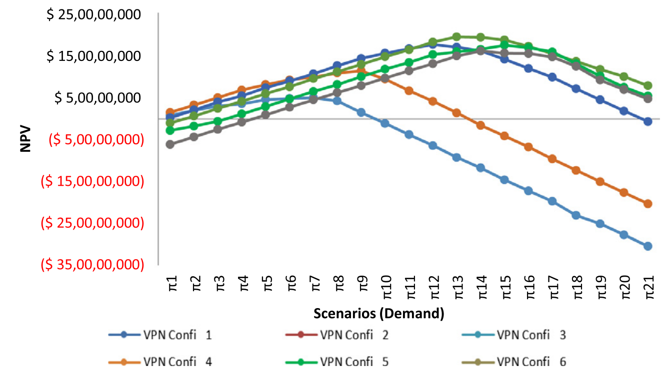
In configurations 3 and 4, a low IRR is observed in low demand scenarios. Since when working with two plants and two distribution centers, more capital is invested in facilities, which generates low cash flow when sales are low. However, as demand increases, the IRR increases to the point where the capacity of the plants and the distribution centers allows it. When the maximum capacity of one of the links that make up the supply chain is reached, unmet demand begins to be generated, which generates penalty costs that affect the cash flows and therefore the IRR.

Configurations 5 and 6 operate with three plants or with a plant with much greater capacity than the others. This decision generates high initial investment that for low demand scenarios cannot be covered generating a lower IRR in comparison to other options. However, in high demand scenarios, it is possible to make better use of its capacity and the earnings already generate higher profitability than the other configurations.

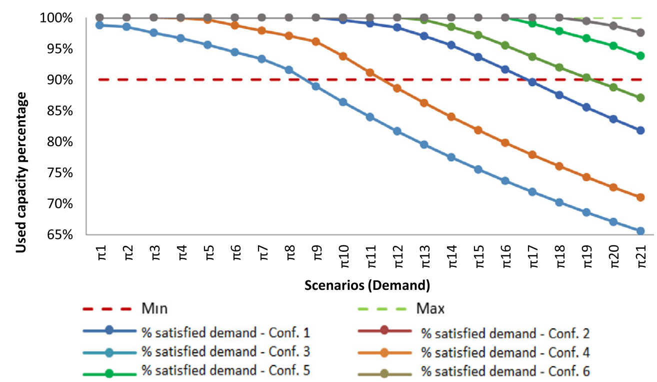
We can say that if there were certainty between the demand values to be found, it could be decided what configuration would be ideal. See Table 4:

However, for this research project, we seek to evaluate which of the configurations is the most robust in all the possible scenarios. To quantify this, we will count the number of scenarios per configuration that exceeds 23.4% for the IRR, minimum value defined for the robustness requirement. The result of this count is presented in Table 5 below:

Table 5 shows that configurations 3 and 4 have the greatest number of scenarios in which the minimum value defined for the robustness requirement (IRR) is exceeded. Consequently, we can say that the most robust configurations for the proposed supply chain are configuration 3 and 4. Configuration 3 has one scenario in minimum demand and one scenario in maximum demand where the IRR is below the minimum value. In configuration 4, the 2 scenarios have a IRR below the minimum value, when demand is low. This can serve as a criterion for deciding on the best configuration. In the case of a downward trend in demand, configuration 3 is better and in the case of an upward trend in demand, it would be more appropriate to select configuration 4. On the other hand, configuration 3 has five scenarios with a higher IRR than configuration 4.



Graph 9. Effects of the perturbation parameter on the NPV.



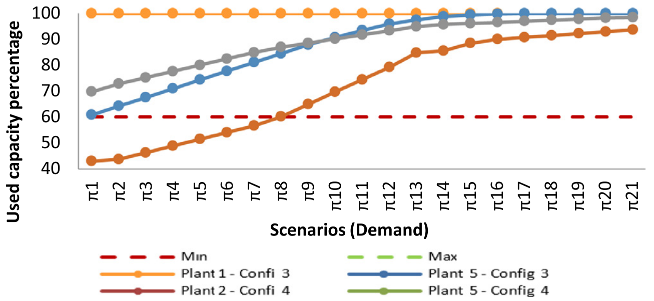
Graph 10. Effects of the perturbation parameter on % of met demand.

Graph 9 shows the effect of the perturbation parameter on the NPV (Net Present Value), which is related to the IRR; since theoretically the calculation of the IRR depends on the NPV in a method known as linear interpolation. Thus, configuration 4 shows that with the minimum demand, it obtains negative values of NPV. It also has the maximum values of NPV in the final scenarios, due to lower investment than configurations 5 and 6. Additionally, it has a greater number of plants and distribution centers. Configuration 3 presents its only negative NPV in the maximum demand scenario, but has a lower NPV in the higher demand scenarios.

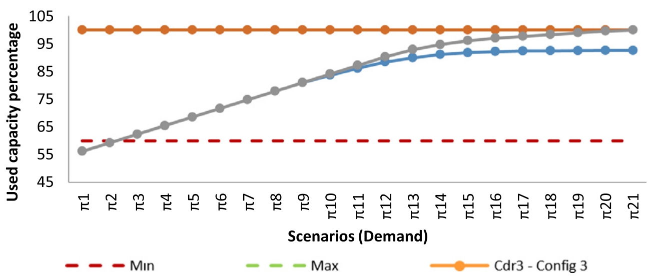
To select one of the two configurations, we decided to analyse the effect of the perturbation parameter on the operating characteristics. In Graph 10, we present the analysis of the met demand.

According to Graph 10, configuration 3 has five scenarios in which it does not meet the minimum met demand of 90%, while configuration 4 only has two scenarios with the same situation. Consequently, configuration 4 can be considered more robust, since they are going to assume less penalty costs. This generates a greater IRR and the NPV in those last scenarios. Although configurations 5 and 6 always meet the performance characteristics of met demand above 90%, they cannot be considered robust, as they do not comply with the robustness parameters established for this study.

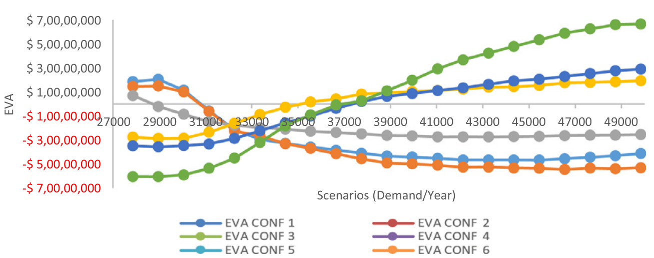
For the analysis of the effect of the perturbation parameter on the used capacity of the plants, we proceeded to analyse only the configurations on which we want to decide. This is done in Graph 11 where we can observe that configuration 3 has a higher percentage in the utilization of its plants in comparison with configuration 4. Although, the plants used in the two configurations



Graph 11. Effects of the disturbance parameter on % utilization of the proposed plants of Configurations 3 and 4.



Graph 12. Effects of the perturbation parameter on the % utilization of the proposed Cdr's of configurations 3 and 4.



Graph 13. Effects of the perturbation parameter on the Economic Value Added (EVA).

are different, it is a guide to decide which configuration is more robust.

Then, we analysed the effect of the disturbance parameter on the used capacity of the distribution centers. Graph 12, which shows that configurations 3 and 4 use the same distribution centers. Configuration 4 has a greater utilization percentage of distribution center 4 than configuration 3. Finally, the use of distribution center 3 is the same in both configurations.

Based on the analyses carried out, we concluded that the most robust configuration for the supply chain proposed is configuration 4, which operates with plants 2 and 5, distribution centers 3 and 4 and disposal center 1. This as in 17 out of the 2i1 possible demand scenarios (Disturbance parameter), configuration 4 exceeds the minimum value of the robustness requirement that is the IRR. Also only in 2 out of the 21 scenarios, met demand below 90% is satisfied. The average of configuration 4 s lower than the current configuration. Likewise, the utilization percentage of the distribution center 4 is greater than the percentage of use of the same distribution center in configuration 3.

Graph 13 shows of the effects of the perturbation parameter on the Economic Value Added for each of the six configurations analysed. We can observe how the first two configurations have positive values only in the first three scenarios. Later, with the increase in demand, their economic values are negative due to non-compliance with demand. In configuration 3, one of the best alternatives, shows to have negative effects in 20 scenarios, when analysing the effects of the disturbance parameter in the IRR and NPV. Despite of generating good results with the IRR and NPV, the net gains produced are lower than the value of the contributions, which generates negative Economic Values Added. Configuration 4, selected as the most robust configuration according to the selected criteria, has 42.8% of its scenarios with negative Economic Value Added levels similar to those established in configuration 5. In configuration 6, the Aggregate Economic Values with scenarios with low demand show lower losses to the shareholders compared with other analysed configurations. However, when the scenarios have a higher demand, the levels of aggregation of value for shareholders are much higher than in the rest of the configurations. On average, configurations 4 and 6 are the only ones that generate Economic Value Added to shareholders. This indicates that measures must be taken to maintain demand levels above 3,600 units per year in order to generate value from the contributions made by the shareholders.

The creation of a new way to evaluate the generation of value by integrating several approaches will allow designing a Supply Chain (CS) that incorporates all its echelons, thus achieving greater control in the execution of processes and financial evaluation.

7. Conclusions

This work was motivated by the impact of economic uncertainty on the financial statement of supply chains. A healthy and viable financial situation provides the necessary funds in a supply chain. These investments must have a satisfactory financial performance. However, these desirable conditions do not always happen in practice and business managers must find a balance. The proposed MINLP design model considers some factors that may originate financial risk. These factors are evaluated from two popular indices, the Net Present Value and the Internal Rate of Return, from the perspective of the increase in Economic Value Added (EVA ^{TM}). The model manages the economic uncertainty, inherent to financial operations, through the system's robustness approach.

The development of this paper demonstrated the possibility of evaluating the robustness of a supply chain by applying the FePIA methodology proposed by Ali et al. [40] having financial indicators as a requirement of robustness. These indicators facilitate the interpretation and measurement of a system, because the results obtained are translated into financial terms. Furthermore, the used indicators allow the supply chain to be evaluated in light of the main financial objective of any type of profit-generating company.

On the other hand, we understood that the definition of the robustness requirement must be very closely linked to the objective pursued by the company. This understanding is relevant, since if the company wishes to have a percentage of total met demand but its goals or performance requirements are financial, it would be pursuing a different objective. As analysed, meeting the total demand requires more investment and therefore more costs that affect the financial indicators. The previous affectation in turn and in turn affecting affects the robustness of the system analysed from this kind of perspective. The previous relation in turn affects the robustness of the system analysed from the financial perspective.

In addition, it was possible to show that there are financial indicators that can be considered as a robustness requirement for a supply chain. Moreover, the same can occur with other types of variables that are established as a requirement of robustness. For this reason, we consider relevant to define criteria and evaluation methods to analyse all the possible options and select an adequate requirement that takes into account the other variables that affect the system.

Mainly financial managers give the final acceptance of an investment project, such as the configuration of a supply chain. This work allows these decision-makers to use financial indicators from the design of the supply chain to determine the impact in the financial performance of the project. This impact can be quantified by using typical project evaluation indicators.

Based on the literature review, we concluded that it is important to consider not only the associated costs in the design of a supply chain and its formulation but also the uncertainty. Real information, that can be quantified, will allow creating more robust configurations from the design of the supply chain. From the preliminary design, logistical and technical requirements, financial criteria for project evaluation can be incorporated to meet the financial requirements of investors and to allow the supply chain to operate in situations of uncertainty such as fluctuations in demand, among others, creating competitive advantages.

On the other hand, it was possible to demonstrate the impact that decisions have regarding the selection of plants, distribution centers, capacities, and costs through the mathematical model proposed and its experimentation under different scenarios. That is, it was evidenced and quantified how the strategic decisions influence the robustness requirement, since a change in one of the variables described above can affect the others and generate costs or operating conditions below the established levels by the investors.

Regarding the simulations, we verified that it is possible to evaluate the level of robustness of a supply chain by means of a software formulation. This is an advantage since you can check multiple options without incurring the costs that would be assumed if you could not test the different resulting configurations. As mentioned earlier, supply chains can be provided or shielded from their design to work in fluctuating situations such as variations in demand or risks that may affect the operation of the system.

For the maximization of the benefit when determining the level of robustness of a supply chain, it is possible to select multiple robustness requirements of different types: financial, capacity, among other considerable variables. The same situation occurs with the perturbation parameters due to there are various risks and conditions that can affect the requirement of robustness and the optimal functioning of the system. Therefore, it must be relevant to consider combinations of robustness requirement and perturbation parameters trying to match the operation to reality to obtain a better analysis. However, it should be noted that there is a high probability that the more robust the system, higher costs must be assumed. If the formulation is performed to optimize an existing supply chain, strategies and methodologies should be established to help quantify existing and future risks, and take into account risks associated.

These risks must include the company sector, regulations, and restrictions by regions achieving a design of the chain more robust. The robustness of a supply chain configuration should not only be limited to selecting the configuration with the best behaviour of the requirements, but also the effect of the perturbation parameters on the operating characteristics should be analyzed. Indeed, a chosen configuration with the best TIR, but with deficient use of plants and distribution centers, could be a wrong decision because if the supply chain is in design can still be modified and analyze changes in the simulation to correct this issue.

Finally, due to the limitations of the proposed model, future research that could enrich the former algorithm with risk exposure methodologies, such as value at risk (VaR), the risk to the downside and stress tests. Other aspects that deserve to be studied in more depth could focus on modeling advanced aspects of financial management, such as "sale and lease" of fixed assets and term contracts of raw materials. In addition, the uncertainty of the demand could be considered as stochastic allowing the use of methodologies like Sample Average Approximation to solve the corresponding problem.

Acknowledgments

The authors thank the editor and the referees for helpful comments and suggestions. This research is supported by grants from Fundación Universitaria Agraria de Colombia (PI180019) research projects.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.omega.2018.09.003.

Appendices

See Tables 6–11.

Table 6
Production capacity of the plants.

	Unit/period
p1	150
p2	562
p3	953
p4	150
p5	157

Table 7
Recovery capacity.

	Unit/period
p1	45
p2	46
p3	48
p4	48
p5	47

Table 8
Distribution capacity (Forward).

	Unit/period
cdr1	180
cdr2	340
cdr3	160
cdr4	708
cdr5	360
cdr6	176

Table 9
Distribution capacity (Reverse).

	Unit/period
cdr1	35
cdr2	35
cdr3	30
cdr4	38
cdr5	38
cdr6	38

Table 10
Disposition capacity of disposal centers.

	Unit/period
cd1	20
cd2	20
cd3	21
cd4	20

Table 11
Other parametric information of the case study.

Parameter	Values for parameters of the mathematical model.	Defined values:
ret_{lt}	Return rate of used products	Values between 5% and 12%
$inip_j$	Initial investment for plant installation	Values from COP 25,161,290 depending on the capacity
$inicdr_k$	Initial investment for distribution center installation	Values from COP 13,516,324 depending on the capacity
$inicd_m$	Initial investment for disposal center installation	Values from COP 20,731,527 depending on the capacity
f_{jt}	Fixed plant operating cost per period	Values from COP 6,541,290 depending on the capacity. It will increase based on the CPI for April for the last five years.
g_{kt}	Fixed distribution center operating cost per period	Values from COP 2,791,765 depending on the capacity. It will increase based on the CPI for April for the last five years.
h_{mt}	Fixed disposal center operating cost per period	Values from COP 3,670,935 depending on the capacity. It will increase based on the CPI for April for the last 5 years
a_{jkt}	Transport cost per unit from plant to distribution center per period	Values from COP 1029 that will increase based on the CPI for April for the last five years.
b_{klt}	Transport cost per unit from distribution center to markets per period	Values from COP 1,040 that will increase based on the CPI for April for the last five years.
e_{kjt}	Transport cost per recovered unit from distribution center to plants per period	Values from COP 1206 that will increase based on the CPI for April for the last five years.
o_{kmt}	Transport cost per disposed unit from distribution center to disposal center per period	Values from COP 1009 that will increase based on the CPI for April for the last five years.
cr_{lkt}	Transport cost per returned unit from markets to distribution center per period	Values from COP 1002 that will increase based on the CPI for April for the last five years.
α_{jt}	Production cost per unit, per plant, per period.	Values from COP 9028 that will increase based on the CPI for April for the last five years.
ρ_{it}	Material purchase cost to supplier per period	Values from COP 2042 that will increase based on the CPI for April for the last five years.
η_{kt}	Used product collection cost in distribution center, per period.	Values from COP 2015 that will increase based on the CPI for April for the last five years.
γ_{mt}	Product disposal cost in disposal center per period	Values from COP 1906 that will increase based on the CPI for April for the last five years.
φ_{lt}	Penalization cost per market per period	Values from COP 51,136, which considers the unit value by unsatisfied demand and also considering an increasing rate between 5% and 10%
pv_{lt}	Sale Price per market per period	Values from COP 53,113 that will increase based on the CPI for April.2017.
λ_{kt}	Recovered product distribution cost in distribution center, per period.	Values from COP 1101 that will increase based on the CPI for April for the last five years.
Ad	Losses average	Scalar (10%)
ir	Interest rate - PVN calculation	Scalar (21%) – Minimum requirement of robustness.
vs	Salvage value	Scalar value (30%)
TR	Tax rate	Scalar value (35%)
PD	Coefficient of demand variation	Scalar value (Between 0 and 100)

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