Universidad del Norte

Faculty of Engineering

Industrial engineering department

Optimization and logistics

Modeling and optimization of the palm oil (*Elaeis guineensis*) supply chain in Colombia

Submitted by:
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A dissertation submitted in fulfillment of
the requirements for being awarded for the
Doctor degree in Industrial Engineering

Directed by
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Barranquilla, 2021

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Abstract

The aim of this research is to develop a quantitative tool that supports decision-makers in the strategic planning of supply chains (SC). The problem to be solved consists in determining the optimal configuration of the palm oil SC, including decisions associated to the number, location and capacity of all the facilities of the SC in a given country; its expansion policy in the planning horizon, means of transportation, production rates, material flow, waste management, and its potential environmental impact.

Bearing this in mind, two mathematical models are presented to address this problem.

The first one is a mixed integer linear programming (MILP) model (section 2.3) applied to the oil palm industry in Colombia (see chapters 3 and 5) that aims to maximize the net present value of its SC in a specific planning horizon. This model includes four types of production facilities: crude palm oil production plants, palm oil refineries, biodiesel production plants, and power plants capable of generating electricity from the palm oil production residual biomass. Besides the main products, crude oil production plants can generate by-products such as palm oil kernel and biomass. In addition, biodiesel production plants produce glycerin, which is considered a waste within this production process.

This model also considers two types of storage: liquid and solid product deposits. Mainland Colombia is divided into 31 regions (known as departments) where production plants of different technology le-

vels can be established. Regarding the transportation of materials between these regions, two types of trucks are considered: one for solid products and another for liquid products. Likewise, two supply and demand scenarios are considered in this model: an increasing demand scenario for two products (electricity and biodiesel), and a constant demand scenario for the same products. Optimization results show that both crude palm oil (CPO) production and biodiesel production plants represent the largest proportion of plants that must be established in those regions with a greater production capacity of fresh fruit bunches (FFB).

On the other hand, the second model solves a multi-objective optimization (MOO) MILP problem (see chapter 5, mathematical model section). It combines the first model with the Life Cycle Assessment (LCA) methodology (see section 2.5) to optimize the palm oil SC in Colombia. The MOO model aims at maximizing the economic benefit of this SC and simultaneously minimizing its environmental impact (measured in “eco-points”). The MOO problem was solved using the epsilon constraint method (see section 2.4). Pareto optimal solutions provide valuable information for the optimal design and configuration of the palm oil SC, in particular the compensations or trade-offs resulting from economic profit, and its environmental impact. The solutions obtained through this model show a more rational distribution of productive units, including the establishment of renewable power plants (see chapter 5).

Acknowledgements

The author is grateful for the support of the Government of Magdalena, the scholarship programme General System of Regalías (SGR) doctorate Nacional Colombia [Not. 672], the Universidad del Norte (Colombia), the CYKLOS research group at the National University of Tucumán (Argentina) and doctors Fernando Daniel Mele, Daniel Cortés Borda, Agustín Barrios Sarmiento and Mildred Domínguez Santiago.

I love you,

Elvira Elisa

Contents

Chapter 1

Introduction

Increased productivity monocultures with low operating costs (e.g. soybean, sugarcane, and palm oil) have globally expanded along with the fight against poverty and hunger discourse. Among these monocultures, oil palm has been widely used as the main raw material for biodiesel production, as well as in the food industry. Notably, the intensive farming of oil palms has led to significant concerns related to the expansion of crops at the expense of the destruction of natural habitats and ecosystems. In addition, the palm oil supply chain (SC) (namely, cultivation, manufacturing, distribution, and marketing of palm oil products) has been severely criticized due to its social adverse effects, including the food versus fuel dilemma [1, 2, 3, 4], and the health problems associated with the intake of saturated fats [5, 6]. However, despite the major environmental and social concerns of the palm oil SC, oil palm plantations keep increasing around the world. By 2050, the current demand for vegetable oils is expected to double [7]. Thus, the palm oil industry requires performing timely actions to mitigate its environmental and social impacts and avoid unsustainable scenarios in the future.

Significant efforts have been made to reduce the social and environmental impacts of this industry in emerging economies such as Cameroon [8] and Indonesia [9, 10, 11], including access to finance for smallholder farmers, the provision of technical support, the sustainable inclusion of smallholder farmers with land titles in the palm oil industry, and the requirement of being Certified as Sustainable Palm Oil producer by the Roundtable on Sustainable Palm Oil (RSPO) in order to reduce the deforestation resulting from oil palm cultivation. These actions are often implemented *a posteriori* on existing (and non-optimal) palm oil SCs. However, an *a priori* and careful designed optimal SC might be an appropriate solution to meet the demand for CPO in emerging markets, while tackling its adverse effects by using resources in an environmentally friendly way. Such difficult task requires studying complex spatial and temporal interactions between the different echelons of the SC, as well as using quantitative tools leading to maximum economic benefits while minimizing the environmental impact.

Another important action to reduce the environmental impacts of this SC is the appropriate management of the residual biomass resulting from its operation. Studies addressing this type of SC propose using mathematical programming models to minimize the effect of poor quality biomass, taking into account the potential locations of storage facilities and biorefineries, as well as the means necessary to transport this product,[12, 13, 14]. On the other hand, LCA is an important tool for monitoring the environmental impact of the palm oil palm SC. The processes involved in the conversion of residual biomass into electricity are sources of greenhouse gas emissions and other air pollutant gases. Studies reporting such impacts [15, 16, 17, 18] present numerical data in different case studies and provide information on the life cycle inventory of this supply chain, particularly in the cultivation and biomass based power generation by thermochemical processes stages. In this regard, the present research proposes a mathematical programming model that optimizes a palm oil supply chain and in which the generation of electricity from residual biomass and an analysis of the environmental impact caused by said generation are included (see chapter 3 and 5).

In the case of Colombia, the fourth biggest producer of palm oil in the world, the palm oil SC has been studied by several research works [19, 20, 21, 22, 23, 24]. However, to the best of the author's knowledge, so far there are no studies addressing the integration of the processes inherent to the palm oil SC (plantation, oil extraction, refining, transportation and distribution) with biofuel production (i.e. biodiesel), the production of alternative energy sources (i.e. cogeneration of electric power using biomass), and the minimization of their environmental impact nationwide. Thus, this dissertation contributes to the state of the art in this field of research by optimizing economic and environmental objectives of the Colombian palm oil SC, while including the generation of electricity from the residual biomass resulting from oil palm fruits. This approach addresses a major issue of the palm industry from the perspective of circular economy. Its results might lead to solutions that simultaneously reduce the volume of waste resulting from this SC and increase the energy sustainability of the palm oil industry (see chapter 5, results and discussion section).

Taking this into account, the aim of this dissertation is to develop a systematic tool based on mathematical programming, multi-objective optimization and Life Cycle Assessment to support the decision-making process in the strategic planning of the palm oil (*Elaeis guineensis*) SC in Colombia. To this end, two mixed integer linear programming (MILP) models (see Chapters 3 and 5, mathematical model section) are developed: (*i*) a single-objective model based on different planning horizons and optimization gaps that seeks to maximize the net present value (NPV) of the whole SC, and (*ii*) a multi-objective optimization (MOO) model that extends the first model to a formulation that aims at maximizing the profitability of the SC and simultaneously minimizing its environmental impact (measured in “eco-points”).

The results obtained with the two optimization models allowed establishing optimal configurations of the SC in terms of the number of plants, warehouses, transportation channels and location, as well as in terms of production, storage and transportation capacities, evidencing a preference for CPO and biodiesel production technologies (see Chapter 3, results and discussion section), and a trade-off between economic and environmental objectives in each Pareto optimal solution (see Chapter 5, results and discussion section). The outcomes of this work provide useful information to define new expansion policies when selecting manufacturing technologies and to decide which points of the Pareto front could result in an appropriate cost-benefit balance, considering the environmental and economic constraints. Furthermore, the models presented here can be used with other types of SC with similar characteristics.

This dissertation is structured as follows: First, the research objectives are presented in section 1.1, and the problem statement is developed in section 1.2. Then, the conceptual elements of the SC management and mathematical programming (sections 2.1 and 2.2), the MOO (section 2.3), the ϵ-constraint method (section 2.4), and the evaluation of the environmental impact through the life cycle assessment methodology (section 2.5) are briefly described in chapter 2. On the other hand, the article entitled "An optimization approach for the design and planning of the oil palm SC in Colombia" is presented in chapter 3 (it should be noted that this paper was published in the Computers & Chemical Engineering journal on December 21, 2020, and has been available online since that day). Additionally, chapter 4 includes the results and discussion of the case study submitted on September 24th, 2020 to the Computers & Chemical Engineering journal, for such data were not finally published in said journal. Chapter 5 presents the results of the MOO model that was submitted on June 28th, 2021 to the Journal of Cleaner Production as a paper entitled "A multi-objective approach for the design and planning of more sustainable oil palm SC". Finally, the conclusions of the research and the possible future work are addressed in chapter 6.

1.1 General objective

The general objective of this dissertation is to develop a mathematical model that allows obtaining the optimal structure of the oil palm SC (*Elaeis guineensis*), in Colombia, at a strategic decision level (design).

Objectives

- Identify the logistics activities associated with production, transformation and final consumer, in the oil palm SC in Colombia.
- Develop, through mathematical programming, a linear integer mixed optimization model (MILP) to determine the optimal configuration of the palm supply chain in Colombia and the associated planning decisions by maximizing profitability.
- Extend the previous optimization model to a multi-objective formulation (MO-MILP) to determine the optimal configuration of the Colombian oil palm supply chain and associated planning decisions, under two criteria: maximizing profitability and minimizing environmental impact.

1.2 Problem Statement

The MILP model of the palm oil SC aims at establishing the optimal structure of the three echelons (production-storage-marketing) of this SC in Colombia. This SC includes a set of production and storage facilities that can be established in different regions of the country. Two types of models were developed: single objective optimization and MOO (chapters 3 and 5, respectively). The first problem can be stated as follows:

Given a fixed time horizon; price of products; production, storage and transportation of materials costs parameters; prevision of the demand for the products; tax rates; types of production plants; the capacity of storage facilities, and the transportation channels; capital investment limits; interest rates; storage periods, and taxes on waste disposal, the objective of the study is to determine the optimal configuration of the palm oil SC and the associated planning decisions that allow maximizing the NPV. These planning decisions include the number, location and capacity of the production plants and storage facilities to be established in each region; their expansion capacity policies for a given price forecast and the demand for the products in the planning horizon; the transportation channels and the vehicles that must be used within the SC network; the material flow, and waste management.

The model contains a geographical discretization of regions of the country, different production and storage technologies, and different means of transportation for the distribution of products. In addition, two supply and demand scenarios are considered: an increasing demand scenario for two products (biodiesel and electricity) and a constant demand scenario for the same products.

In the case of the MOO model, a set of environmental indicators and profitability are optimized. An annual increase in the demand for the two products (biodiesel and electricity) was chosen as the demand pattern (chapter 5, problem statement section).

Chapter 2

Conceptual framework

The objective of this section is to familiarize the reader with the concepts that will be used in 3 and 5. These concepts include the palm oil SC, which shows the context of the problem to be addressed in this research; mathematical programming as an optimization technique for supporting decision-making processes; the MOO, which in this work is used for achieving the optimization of two objectives (an environmental objective and an economic one); the ϵ-constraint method used to address the MOO and the environmental impact model used to identify the shifting environmental burdens in the different phases of the life cycle of the palm oil SC.

2.1 Supply chain of the oil palm *Elaeis guineensis*

The following stages of the palm oil SC were considered in this study: production, storage and transportation. In the production stage, FFB are processed to extract CPO in order to produce biodiesel and refined oils. In the FFB milling process palm kernel oil is a by-product and crude palm kernel oil (CPKO) is extracted. In this process, the residual biomass of the palm is used for generating electricity. Regarding storage, two types of storage are considered: liquid and solid product deposits. In the transportation stage, two types of vehicles are proposed: medium trucks and tank trucks for the transportation of solid and liquid materials, respectively (chapter 3, problem statement section).

Some studies addressing the palm oil SC link the theory with management strategies and practices [25] to identify the environmental and health risks associated with this SC and the way to find, evaluate and use appropriate methods to face such risks. SC management allows for the supervision of the SC operations and the coordination of the parties involved to ensure an efficient and profitable general process. Currently, SC management is a field of research frequently studied, as shown in different works [26, 27].

One of the main risks of the palm oil SC is associated with the cultivation of oil palm stage, since it grows in tropical areas and its farming puts at risk ecosystems with high levels of biodiversity. This threat to tropical ecosystems leads to a socio-environmental issue in the countries where oil palm trees are grown [24],[28],[29],[30]. Deforestation is not the only environmental effect of the life cycle of the palm oil SC, as its other stages also have negative effects on the environment: from the cultivation stage (e.g. the use of fertilizers, or the use of fossil fuels for the operation of agricultural machinery) to the refining process of the extracted products (the release of effluents from milling plants into the environment) [15],[31].

Strategic planning in the palm oil SC is fundamental for the entire value chain. Such planning is not only applicable to the material flow from the cultivation stage to the final consumer, but also to the flow of information between the agents involved with the SC. In this sense, the aim of strategic planning is to identify and evaluate the best options for the acquisition of resources that allow improving the sustainability and competitiveness of the palm oil industry in the long term. For this reason, decision-making models provide a systematic and comprehensive approach to these SCs (as shown in chapters 3 and 5), especially in the assessment of the interactions taking place between the different echelons by means of the several options available between acquisition and resource diversification.

2.2 Mathematical programming

Mathematical programming is a useful tool to solve problems involving not only optimization of a SC in economic terms but also its possible environmental impact, as it facilitates the search for solutions with different objective functions that must be optimized on a feasible set of such objective functions. Mathematical programming is also a useful tool in different industries since it deals with problems that seek to maximize or minimize an objective function $\mathfrak{F}$:

$$\begin{aligned} \min\ & \mathfrak{F} \\ \textit{subject to} & \\ g(x,y) &= 0 \\ h(x,y) &\leq 0 \\ x &\in X,\ y \in Y \end{aligned} \tag{2.1}$$

where $g(x,y)$ represent the equality constraints and $h(x,y)$ the inequality constraints. Decision variables can be continuous ($x \in X$) or integer ($y \in Y$). In the case of a linear programming (LP) problem, the objective function and the constraints are linear, while in non-linear programming (NLP) problems there are continuous variables and one or more non-linear equations. In addition, if a LP problem contains discrete variables together with continuous variables, then it becomes a MILP. Mixed integer non-linear programming problems (MINLP) have at least one non-linear equation and both types of variables. MILP models are developed in this work (see chapters 3 and 5).

2.3 Multi-objective optimization

In mathematical programming some optimization problems can consider more than one objective. This type of formulation where there is more than one criterion can be solved through MOO:

$$\begin{aligned} \min\ \mathfrak{F} = \{\wp_1, \ldots, \wp_k\} \\ \textit{subject to} \\ g(x,y) &= 0 \\ h(x,y) &\leq 0 \\ x &\in X,\ y \in Y \end{aligned} \tag{2.2}$$

In this case, the function is a vector with a set of objective functions $\wp_1, ..., \wp_k$. In the context of our problem, one of the $\wp_k$ objectives represents the economic profitability, while the other, the environmental impact. One of the strategies used to solve MOO problems is ϵ-constraint, which does not have any restriction to obtain non-convex sections of the Pareto front. In the Pareto front, where an $x^{\star} \in X$ point is a Pareto optimal if and only if there is no another $x^{\star} \in X$ point for which $g\,(x)\ \leq\ g\ \ (x^{\star})$ and $g_i\,(x)\ <\ g_i\,(x^{\star})$. That is, $x^{\star}$ point is a Pareto optimal if there no other x value causing the improvement of any of the objectives in relation to the values obtained for $x^{\star}$, but without simultaneously affecting the performance of any other value. This MOO strategy was implemented in this work to optimize the palm oil SC in Colombia (see chapter 5, results and discussion section).

2.4 ϵ-constraint method

The epsilon-constraint method is one of the strategies to solve MOO problems. It consists in turning a MOO model into a single-objective model by reformulating one of more objectives as restrictions that are bound to a set of parameters known as epsilon (ϵ):

$$
\begin{aligned}
\min\ \mathfrak{F} = \{\wp_1\} & \\
subject\ \ to & \\
g(x,y) &= 0 \\
h(x,y) &\leq 0 \\
\wp_k &\leq \epsilon_k \quad k = 2, \ldots, K \\
\underline{\epsilon_k} &\leq \epsilon_k \leq \overline{\epsilon_k} \quad k = 2, \ldots, K \\
x &\in X,\ y \in Y
\end{aligned}
\tag{2.3}
$$

Pareto solutions are obtained by solving problem 2.3 for the different values of ϵ_k. In this work, the economic performance function is considered the main objective in the optimization model, while the environmental indicators of the LCA are regarded as auxiliary constraints. The inferior and superior limits of each parameter ϵ are obtained from the minimization of each objective function. The maximum values of each $\wp_k$ objective are used as superior limits for each ϵ parameter. Therefore, the $\left[\underline{\epsilon_k}, \overline{\epsilon_k}\right]$ intervals are divided into subintervals in a way that the $\mathfrak{F}$ model is solved for each of the limits of these sub-intervals, thus generating a different Pareto solution in each run. A detailed explanation of the model is provided in chapter 5, results and discussion section.

2.5 Methods for evaluating the environmental impact of the palm oil supply chain

The methods for the evaluation of the environmental impact of this SC predict, identify, quantify and assess the environmental impacts of a set of actions and/or activities. In the present work, environmental impact is evaluated through the LCA method [32]. This is a standard method that encompasses four stages: goal and scope definition, life cycle inventory analysis, impact assessment and interpretation of results. Here, the environmental performance of the palm oil SC was measured in “eco-points”. A detailed description of the four phases of the LCA is provided in chapter 5, introduction section.

Chapter 3

An optimization approach for the design and planning of the oil palm supply chain in Colombia

The paper published in the Computers & Chemical Engineering Journal is presented in this chapter; it should be noted that said article has been available online since December 21, 2020. This chapter presents a mixed integer linear programming model aimed at maximizing the expected net present value of the SC, including the electricity provided to the national electrical grid in Colombia. The optimal solution obtained through this model presents a more rational distribution of production, storage, and transportation units. Furthermore, the optimal configuration of the electrical grid based on the combustion of residual biomass, along with its capacity to generate electricity and meet the demand for this good in all the regions of the country is presented.

Computers and Chemical Engineering 146 (2021) 107208

Contents lists available at ScienceDirect

Computers and Chemical Engineering

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

An optimization approach for the design and planning of the oil palm supply chain in Colombia

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ARTICLE INFO

Article history:
Received 24 September 2020
Revised 4 December 2020
Accepted 19 December 2020
Available online 21 December 2020

Keywords:
Oil palm industry
Mixed integer linear programming
Supply chain management
Biomass
Bio-based electricity

ABSTRACT

This article presents a mathematical model to optimize the planning decisions in the Colombian oil palm supply chain (SC). The optimization model consists of a mixed integer linear formulation, aiming at maximizing the expected net present value of the entire SC, including electricity supplied to the national grid by this activity. The model considers different products, types of warehouses, transportation modes, and export options, reflecting as far as possible the current situation of the oil palm industry in Colombia. It sets as free variables the location of the storage and production facilities, their expansion possibilities, and the flows of all feedstock and final products involved in the SC. The model constitutes a quantitative decision-making tool in the area of strategic design and optimal planning of biomass-based SCs. The optimal solution obtained by the model presents a more rational distribution of the production units in comparison with the current situation.

1. Introduction

Fossil fuels represent 80% of energy consumption worldwide, while the share of renewable energies is close to 18% (WBA, 2019). Within this last group, hydroelectric energy continues to be the dominant form; its consumption represents close to 65%, followed by wind-powered with 18%, biomass (combustion of wood, forest material and agricultural biomass) with 9%, solar energy with 7% and geothermal with another 7% (WBA, 2019; Ritchie and Roser, 2017). Within this context, due to its potential to contribute in the sector of renewable energy sources, the oil palm or African palm (*Elaeis guineensis*) is cultivated in various parts of the world to provide oil to the food and biodiesel industries, and to generate electricity.

Palm oil represents almost 25% of the production of vegetable oils in the world, being, after soybean, the second most produced vegetable oil (InfoAgro, 2019). After the oil extraction process, 21-35% (mass) of residual biomass is generated (on the basis of bunches of harvested fruits, fresh fruit bunches, FFB) (Onoja et al., 2018; Loh, 2017; Hambali and Rivai, 2017; Ohimain et al., 2013), whose decomposition constitutes an environmental and public health issue. This biomass (shell, fiber, and empty bunches) has a high potential as a source of renewable energy (Loh, 2017). All this has prompted many oil palm producing countries to use this by-product as an energy source, contributing to the sustainability of the supply chain (SC) of the industry itself (Orjuela-Castro et al., 2019; Carlson et al., 2018; Costa et al., 2017; Boons and Mendoza, 2010).

Colombia is the fourth producer of palm oil in the world, and the first in the Americas (Colprensa, 2018). In this country, the development of the market for biodiesels has been essential to increase local consumption of palm oil, which is close to a million tons and is equivalent to an annual per capita consumption of 20 kg. Furthermore, the cultivation of African palm generates about 1.5 million t/year of lignocellulosic waste (Talero Rojas et al., 2017), which constitutes an opportunity to produce renewable energy from this by-product. Apropos, Colombian policies encourage the integral use of the products of the oil palm, optimization of the value chain, and reduction of logistics costs of the oil palm agroindustry (CONPES, 2007). Law 1715 of 2014 (CNRC, 2014) promotes the integration of nonconventional renewable energies to the national energy system as a necessary mean for sustainable development, the reduction of greenhouse gas emissions, and the assurance of energy supply. In addition, it establishes tax incentives for

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https://doi.org/10.1016/j.compchemeng.2020.107208

Nomenclature

Indices

b	country for exportation
i	materials
l	transportation modes
p	manufacturing technologies
r	region zones
s	storage technologies
t	time periods

Sets

$IB(i)$	set of materials that can be exported
$IL(i,l)$	set of transportation model corresponding to product i
$IM(i,p)$	set of ordered pairs that link main products i to technologies p
$SEP(i)$	set of products that can be sold
$IS(i,s)$	set of ordered pairs that link materials i to storage technologies s

Parameters

$\alpha^{PL}_{p,r,t}$	fixed investment coefficient for technology p
$\alpha^{S}_{s,r,t}$	fixed investment coefficient for storage technology s
$\beta^{PL}_{p,r,t}$	variable investment coefficient for technology p
$\beta^{S}_{s,r,t}$	variable investment coefficient for storage technology s
ξ	electricity conversion factor
$\rho_{p,i}$	material balance coefficient associated with material i and technology p
σ	storage period
τ	minimum desired percentage of the available installed capacity
φ	tax rate
avl_l	availability of transportation mode l
$CapCrop_{r,t}$	total capacity of FFB plantations in region r in time t
$DW_{l,t}$	driver wage
$EL_{r,r'}$	distance between r and r'
$EPR_{i,b}$	price of material i in country b
$\overline{FCI}$	upper limit on the capital investment
FE_l	fuel consumption of transportation mode l
$FP_{l,t}$	fuel price
$FRC_{i,b}$	freight cost of material i
$GE_{l,t}$	general expenses of transportation mode l
ik	interest rate
$LT_{i,r}$	amount of waste and landfill tax
LUT_l	loading/unloading time of transportation mode l
M	big enough scalar
ME_l	maintenance expenses of transportation mode l
$\overline{PCap_p}$	maximum capacity of production technology p
$\underline{PCap_p}$	minimum capacity of production technology p
$\overline{PR_{i,r,t}}$	prices of final products i
$\overline{Q_l}$	maximum capacity of transportation mode l
$\underline{Q_l}$	minimum capacity of transportation mode l
$\overline{Scap_s}$	maximum capacity of storage technology s
$\underline{Scap_s}$	minimum capacity of storage technology s
$\overline{SD_{i,r,t}}$	actual demand of product i in region r in time t
SP_l	average speed of transportation mode l
sv	salvage value
T	number of time intervals
$TCap_l$	capacity of transportation mode l
$\overline{TAE_{i,r,t}}$	exportation capacity of harbors for product i in region r in time t
$TMC_{l,t}$	cost of establishing transportation mode l in period t
U	big enough scalar
$UPC_{i,p,r,t}$	unit production cost
$USC_{i,p,r,t}$	unit storage cost

Variables

$AIL_{i,r,t}$	average inventory level of product i in region r in period t
CF_t	cash flow in time period t
DC_t	disposal cost in time period t
DEP_t	depreciation in time period t
$DTS_{i,r,t}$	delivered amount of material i in region r in period t
$AE_{i,b,r,t}$	amount of exported material i from region r to country b in time t
EC_t	exportation cost in time t
$ES_{i,r,t}$	delivered amount of MWh to region r
FCI	fixed capital investment
FOC_t	facility operating cost in time period t
$FTDC_t$	fraction of the total depreciable capital in time period t
GC_t	general cost in time period t
LC_t	labor cost in time period t
MC_t	maintenance cost in time period t
NE_t	net earnings in time period t
$NP_{p,r,t}$	number of plants with technology p established in region r and time period t
NPV	net present value of SC
$NS_{s,r,t}$	number of storages with storage technology s established in region r and time period t
$NT_{l,t}$	number of transportation units l acquired in time period t
$PCap_{p,r,t}$	existing capacity of technology p in region r and time period t
$PCapE_{p,r,t}$	capacity expansion of technology p in region r and time period t
$PE_{i,p,r,t}$	production rate of material i associated with technology p in region r and time period t
$PE1_{i,r,t}$	quantity of CPO produced by technology T1 if there is a positive surplus of electrical energy in a region r at time t
$PE2_{i,r,t}$	quantity of CPO produced by technology T1 if there is not any surplus of electrical energy in a region r at time t
$PT_{i,r,t}$	total production rate of material i in region r and time period t
$PU_{i,r,t}$	purchase of material i in region r in time t
$Q_{i,l,r,r',t}$	flow rate of material i transported by mode l from region r to region r' in time period t
Rev_t	revenues in time t
$SCap_{s,r,t}$	capacity of storage s in region r in time period t
$SCapE_{s,r,t}$	expansion of capacity of storage s in region r in time t
$ST_{i,s,r,t}$	total inventory of material i in region r stored by technology s in time period t
$TAE_{i,r,t}$	total amount of exported material i from region r in time t
TOC_t	transport operating cost in time period t
$X_{l,r,r',t}$	binary variable equal to 1 if material flow between two regions r and r' is established and 0, otherwise

$Y^1_{r,t}$	binary variable equal to 1 if there is a surplus of electricity in r and t after satisfying the needs plants with T1 technology
$Y^2_{r,t}$	binary variable equal to 1 if there is no a surplus of electricity in r and t after satisfying the needs plants with T1 technology
$W_{i,r,t}$	amount of wastes i generated in region r in time period t

investment in projects from unconventional energy sources: annual income reduction, exemption from value added tax (VAT), exemption from payment of customs duties, and access to an accelerated depreciation regime.

Oil palm SC has been extensively studied. Suksa-ard and Raweewan (2013), for their part, proposed a quantitative tool to support policy makers in decisions related to oil palm plantation assignment, market allocation, and planning of the distribution network. Shukery et al. (2017) formulated a mixed integer linear programming model (MILP) to maximize the economic returns of an eco-industrial city based on palm. Their model allows the selection of a profitable operating system under centralized and decentralized policies. Sembiring et al. (2018) presented a MILP model for a SC planning problem that includes waste processing. Foong et al. (2018) published a multi-period optimization approach to synthesize palm oil milling processes with technically and economically feasible oil recovery technologies focusing on the operation level. Regarding optimization works on the Colombian palm activity, Adarme Jaimes et al. (2011) proposed two mathematical models to optimize the transportation of the FFB, whose objective function minimizes operating costs. The first one describes a general operation and guarantees the delivery of the FFB from internal centers to external locations and from the latter to a manufacturing plant. The second model proposes the single sourcing to ensure that a fruit batch could be sent to only one external location in order to facilitate quality and control actions. Gutiérrez Franco et al. (2011) published a methodology to make decisions based on deterministic and stochastic optimization models, aiming to design a palm oil logistics network oriented particulary to the biodiesel industry. A base scenario is used to determine the opening of biorefineries and the production plan, including the optimum flows of raw material and finished products through the network. Alfonso-Lizarazo et al. (2013) optimized energy and operating costs, and economic benefits derived from the implementation of reverse logistics processes in the oil palm SC. Their results show that integrating practices associated with the implementation of all forward flows and all possible reverse flows, provides significant benefits in comparison with only implementing forward flows. Aranda Pinilla et al. (2014) presented a model for planning the palm oil and biodiesel distribution. The model incluides production and storage, and capacity planning of the biorefineries, while minimizing the total cost of the chain along a certain planning horizon. García-Cóceres et al. (2015) developed a dynamic programming model for the tactical and operational planning of the oil palm SC, which involves the harvest of the fruit and the extraction of crude palm oil (CPO), crude palm kernel oil and cake (CPKO) and cake. The innovative aspects of the model have to do with the way it explicitly defines the number of trips; its dynamic character and specific considerations about integration between the own and rented fleets; and the development of a particular solving procedure.

In Colombia, the oil palm value chain is made up of service and input providers (seeds and seedlings, agrochemicals, services, credits), palm growers, palm oil extractors, palm oil refiners, marketers of final products, and consumers (national and international) Mosquera Montoya and López Alfonso (2017). Different products circulate through this chain (final and intermediate), among which stand out FFB, crude oils extracted from the pulp and the kernel (crude palm oil (CPO) and crude palm kernel oil (CPKO), respectively), biodiesel, and other food and cosmetic products. To these, waste streams such as pressing residues (cake) and empty fruit bunches (EFB) must be added (Fig. 1). Finally, it is important to consider, as a product, the bioenergy that can be produced from the residual biomass generated in 125 the milling processes associated to the extraction of CPO and CPKO (FAO, 2011; 2013).

To produce between 200 and 240 kg of CPO, and between 18–22 kg of CPKO, approximately 18–22 kWh of electricity and 450–550 kg of steam are required, with a residual biomass of 96–130 kg of fiber, 50–90 kg of shell and 120–260 kg of empty bunches (Yañez et al., 2008). Generation potential of electricity produced by biomass is 185 kWh (eight times more than the energy used in the process), which leaves a surplus that can be delivered to the Interconnected System (CNRC, 2014). For Briceño Álvarez et al. (2015), the sale of surplus electricity will allow the agribusiness of oil palm to enter the energy market.

Taking into account the literary background, this work proposes a novel optimization approach for the design of the oil palm SC in Colombia. Unlike previous research, this model of optimization includes the production of bioenergy that, as far as the authors know, has not been integrated into an optimal design model for the national palm SC. There are other types of industries that are part of the oil palm SC, however, they are not taken into account due to their low percentage of participation Fedepalma (2020). In this article, a MILP model of optimization, that integrates different oil extraction and refining processes, production of biodiesel, and cogeneration of electrical energy at the national level, is developed. The model contains a geographic discretization of regions, different production and storage technologies, and different modes of transport for the distribution of the products. The objective function of the model is the maximization of the net present value (NPV) of the SC along a period of five years.

Solving this optimization problem provides a guiding strategy on the distribution of resources, the concentration of efforts, and how to direct the economy of this sector towards the optimum. The developed model has its origin in the one presented by Guillén-Gosálbez et al. (2010) for the design of the hydrogen SC in the UK, and the ones by Mele et al. (2011), for sugarcane ethanol in Argentina and by Kostin et al. (2018), for bioethanol in Brazil.

The article is structured as follows: Section 2 presents the problem statement; Section 3 introduces the mathematical model; Section 4 describes the case study as developed for the reality of Colombia, but adaptable for other geographic contexts. The results of the case study are discussed in Section 5. Finally, the conclusions of the study and possible future research directions are offered in Section 6.

2. Problem statement

The structure of the oil palm SC studied in this article is presented in Fig. 2. As can be seen, it includes the set of palm plantations in Colombia, production and storage facilities for each product, and end markets, with the corresponding distribution channels. Thus, the design problem of this SC can be formally stated as follows.

Given a fixed time horizon, prices of products, parameters of the costs of production, storage and transportation of materials, forecasts of product demand, tax rates, plant capacities, warehouses and transportation channels, capital investment limits, interest rates, storage period and tax on waste disposal; the objective of the study is to determine the configuration of the oil palm SC in Colombia, and the associated planning decisions that maxi-

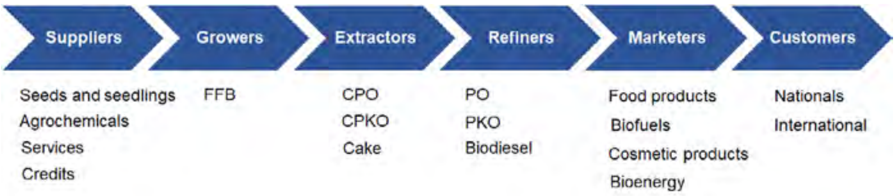

Fig. 1. Oil palm value chain outline, adapted from Mosquera Montoya and López Alfonso (2017).

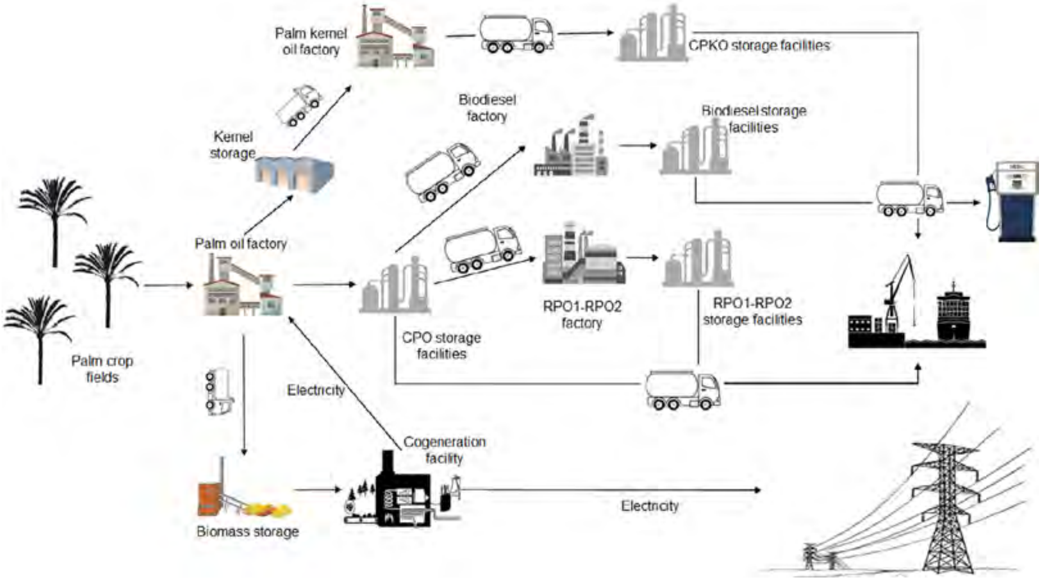

Fig. 2. Structure of the oil palm SC in the Colombian case study including potential electricity generation.

mize NPV. Decisions to be made include the number, location, and capacity of the production plants and warehouses that will be installed in each region; their capacity expansion policy for a given price and demand forecast; transportation links and modes to be established in the network; and flow of raw material, final products, and waste.

A set of regions is considered, which in this case have coincided with the Colombian departments. Each region has a known production capacity for each time interval in the total horizon. Details of production, storage, and transportation are presented below:

Production. The palm fruit (FFB) is made up of empty bunches, exocarp or epicarp, mesocarp or pulp (where CPO is housed), endocarp or shell and endosperm or kernel. The FFB is crushed (T1 technology) (see Fig. 3) to extract CPO, leaving the kernel as a by-product. CPKO is extracted from the kernel (T2 technology). It is also considered the possibility of installing other plants to industrialize CPO to produce biodiesel (T3 technology), and refined oils as olein (refined palm oil 1, RPO1), using T4 technology, and stearin (refined palm oil 2, RPO2), using T5 technology. T1 technology also generates solid residual biomass with high calorific value, usable to be burned in boilers. This biomass residual is separated as part of two mixtures: biomass1 y biomass2. In biomass1, the epicarp, the exhausted pulp, and the endocarp predominate; meanwhile, in biomass2, empty bunches do. This distinction of biomass is done taking into account the study carried out by Nasution et al. (2014). T6 technology uses biomass1 and T7 technology, biomass2 to generate electricity by combustion. The surplus of electricity (electric power, EP), that is, that which is not consumed by T1 technology for its own operation, can be delivered to the Interconnected System (see Fig. 4). The proposed model considers, then, 12 products in total, between raw materials, intermediate products, final products, and by-products: FFB, CPO, CPKO, RPO1, RPO2, biodiesel, kernel, cake, biomass1, biomass2, glycerine and EP.

Storage. The model considers two types of storage, distinguishing between liquid and solid product deposits. For both, it considers the possibility of installation and expansion in each period with the associated capital and operating costs. There are no storage facilities for the FFB, as it must be transported to the factory to be processed within 24 hours after harvest (Sharif et al., 2017).

Transportation. The model proposes two types of vehicles: medium trucks for kernel, biomass1 and biomass2, and tank trucks for liquid products such as CPO, CPKO, RPO1, RPO2 and biodiesel. For any of the means of transportation, the model considers capital and operating costs, with maximum and minimum limits of capacity.

3. Mathematical model

3.1. General constraints

The constraints for the developed model for optimal planning of the oil palm industry in Colombia are described below:

3.1.1. Mass balance

Eq. (1) represents the general mass balance, which applies to all products, except electricity. For each material i, the inventory maintained in region r in the previous period ($ST_{i,s,r,t-1}$), plus the amount of produced product ($PT_{i,r,t}$), the amount of purchased raw material ($PU_{i,r,t}$) and the inflow from other regions of the SC ($Q_{i,l,r',r,t}$) must be equal to the stored quantity of i in period t ($ST_{i,s,r,t}$), added to the quantity delivered to customers ($DTS_{i,r,t}$),

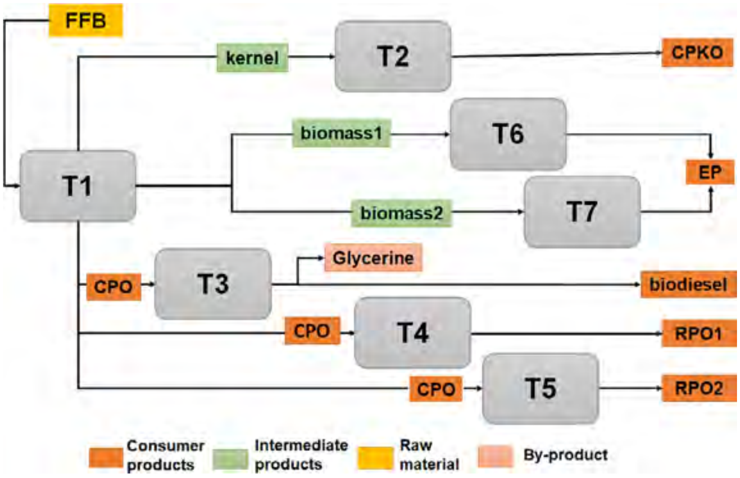

Fig. 3. Interrelationships between the different palm-based products and processing technologies considered in this study.

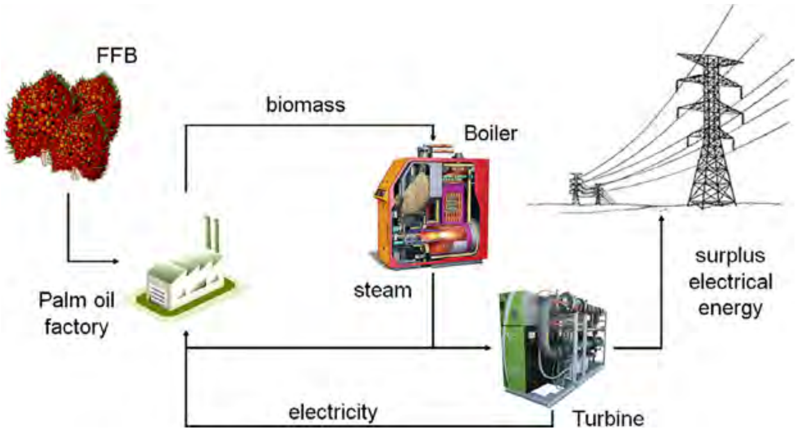

Fig. 4. Process of generating electricity from biomass.

plus the sum of the outflows to other regions ($Q_{i,l,r',r,t}$) the amount of i disposed of as waste ($W_{i,r,t}$) and the quantity of exported product i ($TAE_{i,r,t}$). The set $IS(i,s)$ links each type of storage with the products i that can be stored in said type, while $IL(i,l)$ links product i with its corresponding transportation mode l.

$$\sum_{s\in IS(i,s)} ST_{i,s,r,t-1} + PT_{i,r,t} + PU_{i,r,t} + \sum_{l\in IL(i,l)} \sum_{r\neq r'} Q_{i,l,r',r,t}$$
$$= \sum_{s\in IS(i,s)} ST_{i,s,r,t} + DTS_{i,r,t} + \sum_{l\in IL(i,l)} \sum_{r\neq r'} Q_{i,l,r',r,t} + W_{i,r,t} + TAE_{i,r,t}$$
$$\forall i, r, t \;\; \neq \mathrm{EP} \qquad (1)$$

Eq. (2) indicates that the quantity of products delivered to final consumers must be less than, or equal to, the demand in each region r and time t ($SD_{i,r,t}$). With this, the model is not obliged to satisfy the demand, but to produce whatever is necessary to maximize profit without exceeding a maximum investment limit, as will be seen later.

$$DTS_{i,r,t} \leq SD_{i,r,t} \quad \forall i, r, t \;\; i \neq \mathrm{EP} \qquad (2)$$

3.1.2. Production

Eq. (3) allows us to calculate the total production of material i in each region r and time t ($PT_{i,r,t}$) by adding the production of i that is obtained with each technology p in the same region and period ($PE_{i,p,r,t}$).

$$PT_{i,r,t} = \sum_{p} PE_{i,p,r,t} \quad \forall i, r, t \qquad (3)$$

In Eq. (4), the by-product and raw materials production rates for each of the technologies are calculated, using material balance coefficients $\rho_{p,i}$ and the production rates of the main products. Positive coefficients indicate products, by-products, and residues, and negative coefficients indicate raw materials for each technology. $IM(i,p)$ defines which is the main product i associated with each production technology p.

$$PE_{i,p,r,t} = \rho_{p,i} PE_{i',p,r,t} \quad \forall i, p, r, t \quad \forall i' \in IM(i,p) \qquad (4)$$

The generation of electricity is modeled as follows. The amount of electrical energy consumed by the production process of CPO (T1 technology) is calculated based on the amount of CPO produced and is expressed as $\xi \cdot PE_{\mathrm{CPO,T1},r,t}$ where $PE_{\mathrm{CPO,T1},r,t}$ represents the amount of CPO produced with T1 technology in the region r and time t, and ξ is the conversion factor from CPO to electrical energy (ξ has units of $\mathrm{MW(t\ CPO)}^{-1}$).

The amount of electrical energy that can be sold to the Interconnected System ($ES_{\mathrm{EP},r,t}$) is the surplus between the total amount generated by combustion of biomass1 and biomass2 in a region r and period t ($PT_{\mathrm{EP},r,t}$), minus that consumed by the operation of type T1 plants ($\xi \cdot PE_{\mathrm{CPO,T1},r,t}$), as expressed by Eq. (5).

$$ES_{\mathrm{EP},r,t} = PT_{\mathrm{EP},r,t} - \xi PE_{\mathrm{CPO,T1},r,t} \quad \forall r, t \qquad (5)$$

The total amount of electricity generated by the combustion of biomass1 and biomass2 ($PT_{\mathrm{EP},r,t}$) results from the application of Eq. (3) with $i = \mathrm{EP}$, being $p = \mathrm{T6, T7}$. The amount of CPO produced in plants with T1 technology ($PE_{i,p,r,t}$) is formed by the sum of two terms, Eq. (6). $PE1_{i,p,r,t}$ represents the amount of CPO that is produced with T1 in region r and time t, if there is a surplus of electrical energy in that region and time, and $PE2_{i,p,r,t}$, if there is no such surplus.

$$PE_{i,p,r,t} = PE1_{i,p,r,t} + PE2_{i,p,r,t} \quad \forall r,t \quad i = \text{CPO}, \ \ p = \text{T1} \tag{6}$$

The existence of the two terms in Eq. (6) is mutually exclusive, which is modeled by associating them to two binary variables $Y^1_{r,t}$ and $Y^2_{r,t}$, such that $Y^1_{r,t} = 1$, if there is a surplus of electricity in r and t after having satisfied the needs of plants with T1 technology, and $Y^2_{r,t} = 1$, if there is not such a surplus of electricity.

$$PE1_{i,p,r,t} \le UY^1_{r,t} \qquad i = \text{CPO}, \ \ p = \text{T1}$$
$$PE2_{i,p,r,t} \le UY^2_{r,t} \qquad i = \text{CPO}, \ \ p = \text{T1}$$

$$Y^2_{r,t} = 1 - Y^1_{r,t}, \ \ \forall r,t \tag{7}$$

In Eqs. (7), U is an arbitrarily large scalar. Note that expressions (6) and (7) only apply for $i =$ CPO and $p =$ T1.

The amount of electrical energy delivered to the network in each region r and time t ($DTS_{\text{EP},r,t}$) is equal to the surplus ($ES_{i,r,t}$), if this surplus exists ($Y^1_{r,t} = 1$), and zero otherwise, that is, when the energy generated by cogeneration plants (T6 and T7) is completely consumed by CPO producing plants ($Y^2_{r,t} = 1$). This situation is modeled *via* the constraints (8). M is an arbitrarily large number corresponding to a *big-M* type formulation (Chinneck, 2008).

$$ES_{i,r,t} - MY^2_{r,t} \le DTS_{i,r,t} \le ES_{i,r,t} + MY^2_{r,t} \qquad i = \text{EP}$$
$$DTS_{i,r,t} \le M(1 - Y^2_{r,t}) \tag{8}$$

The production rate of i with technology p, in region r, is limited between a minimum and a maximum value of capacity, according to Eq. (9). The lower limit is obtained by multiplying the continuous variable $PCap_{p,r,t}$ (existing capacity) by a value τ between 0 and 1. The upper limit is the capacity itself ($PCap_{p,r,t}$).

$$\tau PCap_{p,r,t} \le PE_{i,p,r,t} \le PCap_{p,r,t} \quad \forall i,p,r,t \tag{9}$$

Eq. (10) indicates that the expandability of the technologies in period t ($PCapE_{p,r,t}$)added to the production of the previous period, determines the current production capacity in period t.

$$PCap_{p,r,t} = PCap_{p,r,t-1} + PCapE_{p,r,t} \quad \forall p,r,t \tag{10}$$

The inequalities (11) represent the expansion capacity of the technologies $PCapE_{p,r,t}$, also between upper and lower limits, which are calculated from the number of plants installed in the region ($NP_{p,r,t}$) and the minimum ($\underline{PCap_p}$) and the maximum ($\overline{PCap_p}$) values of the capacity of each technology p.

$$\underline{PCap_p} NP_{p,r,t} \le PCapE_{p,r,t} \le \overline{PCap_p} NP_{p,r,t} \quad \forall p,r,t \tag{11}$$

The purchase of raw material (FFB) is constrained in Eq. (12), which is limited by the oil palm production capacity in each region r, in time interval t.

$$PU_{i,r,t} \le CapCrop_{r,t} \qquad i = \ \text{FFB}, \ \ \forall r,t \tag{12}$$

3.1.3. Storage

For any region r, the capacity of a storage technology s, for any time t, is equal to the previous storage capacity plus the expansion capacity ($SCapE_{s,r,t}$) of the current period (Eq. (13)).

$$SCap_{s,r,t} = SCap_{s,r,t-1} + SCapE_{s,r,t} \quad \forall s,r,t \tag{13}$$

Eq. (14) shows that storage capacity is calculated using the number of warehouse facilities in region r ($NS_{s,r,t}$), and is found between a minimum capacity ($\underline{SCap_s}$) and a maximum capacity ($\overline{SCap_s}$) of storage, for each storage technology.

$$\underline{SCap_s} NS_{s,r,t} \le SCapE_{s,r,t} \le \overline{SCap_s} NS_{s,r,t} \quad \forall s,r,t \tag{14}$$

Inequality (15) shows that storage capacity must be greater than the total inventory ($ST_{i,s,r,t}$) of products stored by the technology s, during the time period t.

$$\sum_{i \in IS(i,s)} ST_{i,s,r,t} \le SCap_{s,r,t} \quad \forall s,r,t \tag{15}$$

The average inventory level ($AIL_{i,r,t}$) expected to be maintained throughout the length of the steady-state operation, can be observed in Eq. (16), and is given by the storage period σ and the amount delivered to clients.

$$AIL_{i,r,t} = \sigma DTS_{i,r,t} \quad \forall i,r,t \quad con \quad i \ne \text{EP} \tag{16}$$

The classic SC management approach (Simchi-Levi et al., 2008) pursues to avoid the problem of fluctuations between supply and demand of products i. This approach consists of setting the storage capacity in region r and time t to a value greater than, or equal to, twice the average inventory for that product, as shown in Eq. (17).

$$2AIL_{i,r,t} \le \sum_{s \in IS(i,s)} SCap_{s,r,t} \quad \forall i,r,t \quad con \quad i \ne \text{EP} \tag{17}$$

3.1.4. Transportation

Inequality (18) limits the flow of materials transported between two regions using the minimum ($\underline{Q_l}$) and maximum ($\overline{Q_l}$) limits of each type of means of transportation l. Eq. (19) defines the binary variable $X_{l,r,r',t}$ which takes the value of 1 if there is a transportation route between two regions r and r', and 0 otherwise.

$$\underline{Q_l} X_{l,r,r',t} \le \sum_{i \in IL(i,l)} Q_{i,l,r,r',t} \le \overline{Q_l} X_{l,r,r',t} \quad \forall l,t,r,r' \quad (r \ne r') \tag{18}$$

$$X_{l,r,r',t} + X_{l,r',r,t} = 1 \quad \forall l,r,r' \quad (r \ne r') \tag{19}$$

Material i can also be exported by any region with port capacity. Eq. (20) indicates that the quantity of exported material cannot exceed port capacity ($\overline{TAE}_{i,r,t}$). This parameter has a non-zero value for regions where international ports are located.

$$TAE_{i,r,t} \le \overline{TAE}_{i,r,t} \quad \forall i,r,t \tag{20}$$

The quantity of exported materials ($TAE_{i,r,t}$) that appears in the balance mass Eq. (1), is the sum of all product flows i sent from region r to country b ($AE_{i,b,r,t}$) (Eq. (21)).

$$TAE_{i,r,t} = \sum_b AE_{i,b,r,t} \quad \forall i,r,t \tag{21}$$

3.2. Objective function

The NPV is one of the most used indicators when evaluating long-term investment projects, and it can be calculated according to Eq. (22), that is, sum of each discounted cash flow obtained in each interval of time t, as ik represents the discount rates.

$$NPV = \sum_t \frac{CF_t}{(1+ik)^{t-1}} \tag{22}$$

The cash flow (CF_t) of Eq. (22), in each period of time, is obtained from the net earnings (NE_t), and the fraction of the total depreciable capital ($FTDC_t$) corresponding to that period (Eq. (23)).

$$CF_t = NE_t - FTDC_t \quad t = 1, \ldots, \text{T} - 1 \tag{23}$$

Eq. (24) calculates the cash flow for the last period of time ($t =$ T), the model assumes that part of the fixed capital investment can be recovered at the end of the time horizon. sv is the residual value at the end of the time horizon.

$$CF_t = NE_t - FTDC_t + svFCI \quad t = \text{T} \tag{24}$$

Net earnings are calculated as the difference between earnings (Rev_t), the operating costs of production plants and warehouses (FOC_t) and transportation cost (TOC_t), where φ represents the tax rate and DEP_t stands for the depreciation term, as shown in Eq. (25).

$$NE_t = (1-\varphi)(Rev_t - FOC_t - TOC_t) + \varphi DEP_t \qquad \forall t \tag{25}$$

Income is obtained from the number of final products sold ($DTS_{i,r,t}$) multiplied by the corresponding prices ($PR_{i,r,t}$) plus the quantity of exported products ($AE_{i,r,b,t}$) multiplied by the international prices according to the country of destination b ($EPR_{i,b}$), $b \neq$ Colombia, (Eq. (26)). The set of materials i that can be sold domestically and abroad are represented by $SEP(i)$ and $IB(i)$, respectively.

$$Rev_t = \sum_{i\in SEP(i)} \sum_{g} DTS_{i,r,t} PR_{i,r,t} + \sum_{i\in IB(i)} \sum_{r} \sum_{b} AE_{i,r,b,t} EPR_{i,b} \quad \forall t \tag{26}$$

In Eq. (27), the operating cost of the facilities is obtained by multiplying the unit cost of production ($UPC_{i,p,r,t}$) by the corresponding production rates and the unit cost of storage ($USC_{i,s,r,t}$) times the average inventory level. This cost also includes the cost of waste disposal (DC_t).

$$\begin{aligned} FOC_t = & \sum_{i} \sum_{r} \sum_{i\in IM(i,p)} UPC_{i,p,r,t} PE_{i,p,r,t} \\ & + \sum_{i} \sum_{r} \sum_{i\in IS(i,s)} USC_{i,s,r,t} AIL_{i,r,t} + DC_t \quad \forall t \end{aligned} \tag{27}$$

where DC_t is obtained from the generated waste stream ($W_{i,r,t}$) multiplied by the cost of treatment or the tax on discharges ($LT_{i,r}$):

$$DC_t = \sum_{i} \sum_{r} W_{i,r,t} LT_{i,r} \quad \forall t \tag{28}$$

Eq. (29), is used to evaluate the operating cost of transportation (TOC_t). This variable considers fuel costs (FC_t), labor cost (LC_t), maintenance (MC_t), general expenses (GC_t) and exportation expenses (EC_t). The description of each of these terms is presented in Eqs. (30)–(34).

$$TOC_t = FC_t + LC_t + MC_t + GC_t + EC_t \quad \forall t \tag{29}$$

Fuel costs are calculated according to Eq. (30):

$$FC_t = \sum_{r} \sum_{r'\neq r} \sum_{l} \sum_{i\in IL(i,l)} \left(\frac{2EL_{r,r'}}{FE_l} \cdot \frac{Q_{i,l,r,r',t}}{TCap_l} \right) FP_{l,t} \quad \forall t \tag{30}$$

The factor in parentheses represents the amount of fuel used, where $2EL_{r,r'}$ is the distance traveled in each round trip between regions r and r', FE_l s fuel consumption by transportation mode l, $Q_{i,l,r,r',t}$ represents the flow rate of the material and $TCap_l$ denotes the capacity of transportation mode l. $FP_{l,t}$ is the price of fuel.

Eq. (31) shows that the driver's salary ($DW_{l,t}$) multiplied by the total delivery time (term shown in brackets) allow calculating the cost of transportation labor. The parameters LUT_l and SP_l denote the upload/download time and the average speed of transportation mode l, respectively.

$$LC_t = \sum_{r} \sum_{r'\neq r} \sum_{l} DW_{l,t} \sum_{i\in IL(i,l)} \left[\frac{Q_{i,l,r,r',t}}{TCap_l} \left(\frac{2EL_{r,r'}}{SP_l} + LUT_l \right) \right] \quad \forall t \tag{31}$$

Maintenance cost represents the general maintenance of the transportation units and is a function of the cost per unit of distance traveled (ME_l). The total route is given by Eq. (32).

$$MC_t = \sum_{r} \sum_{r'\neq r} \sum_{l} \sum_{i\in IL(i,l)} ME_l \frac{2EL_{r,r'} Q_{i,l,r,r',t}}{TCap_l} \quad \forall t \tag{32}$$

General expenses (Eq. (33)) are obtained by multiplying the general unitary expenses ($GE_{l,t}$) by the number of transportation units ($NT_{l,t}$). The former includes transportation insurance, license and registration fees, and outstanding debts.

$$GC_t = \sum_{l} \sum_{t'\leq t} GE_{l,t} NT_{l,t'} \quad \forall t \tag{33}$$

Exportation expenses (EC_t) are calculated in Eq. (34), taking into account the quantity of products sent from the region r to country b and the unit freight cost ($FRC_{i,b}$).

$$EC_t = \sum_{i\in IB(i)} \sum_{r} \sum_{b} AE_{i,r,b,t} FRC_{i,b} \qquad \forall t \tag{34}$$

To calculate depreciation, the straight-line method is used (Towler and Sinnott, 2012) as Eq. (35) shows.

$$DEP_t = \frac{(1-sv)FCI}{T} \quad \forall t \tag{35}$$

where FCI (Eq. (36)) represents the total investment of capital, determined by capacity expansions carried out in plants and warehouses, as well as purchases of transportation units over the time horizon.

$$\begin{aligned} FCI = & \sum_{p} \sum_{r} \sum_{t} \left(\alpha^{PL}_{p,r,t} \cdot NP_{p,r,t} + \beta^{PL}_{p,r,t} \cdot PCapE_{p,r,t} \right) \\ & + \sum_{p} \sum_{r} PE2_{\mathrm{CPO,T1},r,t} \cdot PR_{\mathrm{EP},r,t} \cdot \xi \\ & + \sum_{s} \sum_{r} \sum_{t} \left(\alpha^{S}_{s,r,t} \cdot NS_{s,r,t} + \beta^{S}_{s,r,t} \cdot SCapE_{s,r,t} \right) \\ & + \sum_{l} \sum_{t} NT_{l,t} \cdot TMC_{l,t} \end{aligned} \tag{36}$$

The parameters $\alpha^{PL}_{p,r,t}$, $\beta^{PL}_{p,r,t}$ are the fixed and the variable capital costs of plants, respectively. In the same way, $\alpha^{S}_{s,r,t}$, $\beta^{S}_{s,r,t}$ are the fixed and the variable capital costs, respectively, of warehouses. $PR_{\mathrm{EP},r,t}$ is the price of electricity, which multiplies $\xi \cdot PE2_{\mathrm{CPO,T1},r,t}$ if the energy generated by the combustion of biomass has not been enough to satisfy the consumption of plants with technology T1. $TMC_{l,t}$ is the investment cost related to the acquisition of transportation units of mode l. The average number of trucks required to attend the flow between different regions ($NT_{l,t}$) is calculated by the flow of products between regions, the availability of transport (avl_l), the capacity of the shipping containers, the average distance traveled between regions, and the average speed and the time of loading/unloading, as presented in inequality (37):

$$\sum_{i\in IL(i,l)} \sum_{r} \sum_{r'\neq r} \sum_{t} \frac{Q_{i,l,r,r',t}}{avl_l TCap_l} \left(\frac{2EL_{r,r'}}{SP_l} + LUT_l \right) \leq \sum_{t\leq T} NT_{l,t} \quad \forall l \tag{37}$$

The total amount of the capital investment is restricted to an upper limit, as indicated by inequality (38):

$$FCI \leq \overline{FCI} \tag{38}$$

The cost of capital is uniformly distributed over time, according to the Eq. (39) to determine the amortization term ($FTDC_t$)

$$FTDC_t = \frac{FCI}{T} \quad \forall t \tag{39}$$

Finally, the general problem formulation can be expressed, in a compact manner, as follows:

$$\max_{(x,X,N)} NPV \tag{40}$$

subjected to constraints (1)–(39)

$$x \subset \mathbb{R}, X \subset \{0,1\}, N \subset \mathbb{Z}^{+}$$

where x represents the continuous variables of the problem (capacity expansions, production rates, inventory levels, and input flows), X represents the binary variables (that is, the existence of transport links and logical variables related to the flow of electrical energy), and N represents the positive integer variables which, in this case, are the number of plants, storage facilities, and transport units of each kind.

4. Case study

To apply the model, 31 of the 32 departments in which Colombia is administratively divided were considered. The archipelago of San Andrés, Providencia y Santa Catalina was excluded due to its lack of relevance to oil palm industry. The multi-period model was applied for a time horizon of 5 years. Each of these regions has an internal demand associated with the four main products (RPO1, RPO2, biodiesel, and electrical energy). In the case study, RPO1, RPO2, biodiesel, and electrical energy are considered to be sold only in the internal market; and that, in addition, CPO, CPKO, RPO1, RPO2, and biodiesel are exportable, without allocation of external demand. Two scenarios are studied that vary according to the demand pattern. In the first scenario, the demand for RPO1, RPO2, biodiesel, and EP products is constant (constant demand, CD) throughout the time horizon. In the second one, the hypothesis that arises is an increasing demand (ID) for two of the products: an increase of 15% for biodiesel, and 10% in EP, for each year of the time horizon.

Table 1 shows the national demand for final products and the production capacity of FFB (t/year) in each region (Fedepalma, 2019), while Table 2 shows the distances between regions (Google maps, 2020). In the case of the demand for electrical energy, the information was taken from the Ministry of Mines and Energy of Colombia (MME-UPME, 2019). Table 3 presents the maximum and minimum limits of the production capacity of the main products in each technology, and the coefficients of balance of input for the different technologies. Table 4 presents the parameters used to calculate capital and operating costs for the different transportation modes. The upper limit of the investment capital is set at USD 25 billion.

Table 5 shows the parameters that are used to evaluate the capital costs of the different production technologies, while Table 6, indicates those used to evaluate the capital costs for different storage technologies. The unit costs of production for CPO, CPKO, RPO1, RPO2, biodiesel, and EP are 75, 25, 18, 18, 66, and 17 USD/t, respectively. The unit storage cost is 1.5 USD/(t year) for all types of materials. The tax rate (φ), the residual value (sv) and the interest rate (ik) are 0.1, 0.2 and 0.19, respectively. Finally, the landfill tax is equal to 0.05 USD/t, according to Law 99 of 1993 (CNRC, 1993).

To solve the model, GAMS is used with CPLEX on a PC, with an Intel (R) Core (TM) i5-4200U processor, 8 GB RAM and CPU@1.60 GHz. The model includes 110,448 equations, 91,847 simple variables, and 9,610 discrete variables. The MILP was solved to an optimality gap of less than 2%, and a CPU time of about 194 h.

5. Results and discussion

The optimal configuration achieved by the proposed model - for both scenarios- was compared with the current configuration published by different Colombian organizations: SISPA by Fedepalma (2019), the Colombian Ministry of Energy (MME-UPME, 2019), the National Federation of Biofuels of Colombia (Fedebicombustibles, 2020) and the National Agency for Infrastructure (ANI, 2020).

5.1. Constant demand scenario

If compared to the current situation, the model proposes to install fewer plants of T1 technology (28). For the production plants of biodiesel (T3), the model raises the possibility of installing 21 plants, less than the 52 registered in the last census, carried out in 2011 (Fedepalma, 2019). For the production of biodiesel (T3), data

Table 1
Domestic demand of final products and FFB production capacity (t/year).

Region (state)	Final product demand					FFB production capacity
	Identifier	RPO1	RPO2	biodiesel	EP	
Amazonas	R01	24020	24020	3328	0	0
Antioquia	R02	27628,7	24869,1	237120,6	4981500	1061386,3
Arauca	R03	24020	24020	158080,4	1683800	0
Atlántico	R04	24020	24020	169728,4	2488714,28	0
Bolívar	R05	40386,9	27871	169728,4	2488714,3	4813787,5
Boyacá	R06	24020	24020	237120,6	1683800	0
Caldas	R07	24020	24020	79040,2	921000	0
Caquetá	R08	24029,6	24022,3	79040,2	1087666,7	2835,4
Casanare	R09	62656	33110,8	237120,6	1683800	11363520,7
Cauca	R10	24020	24020	178048,5	687333,3	0
Cesar	R11	90609,1	39688	169728,4	2488714,3	19585017,2
Chocó	R12	24020	24020	237120,6	4981500	0
Córdoba	R13	24020	24020	169728,4	2488714,3	0
Cundinamarca	R14	24398,4	24109	237120,6	9454500	111293,4
Guainía	R15	24020	24020	3328	0	0
Guaviare	R16	24020	24020	3328	4727250	0
Huila	R17	24020	24020	79040,2	1087666,7	0
La Guajira	R18	24020	24020	169728,4	2488714,3	0
Magdalena	R19	68149	34403,3	169728,4	2488714,3	12979101,4
Meta	R20	127917,1	48466,4	237120,6	4727250	30557977,5
Nariño	R21	35295,5	26673	178048,5	687333,3	3316319,4
Norte de Santander	R22	49173,1	29938,4	158080,4	1683800	7397980,2
Putumayo	R23	24020	24020	178048,5	687333,3	0
Quindío	R24	24020	24020	79040,2	921000	0
Risaralda	R25	24020	24020	79040,2	921000	0
Santander	R26	69411,6	34700,4	158080,4	1683800	13350484
Sucre	R27	24020	24020	169728,4	2488714,3	0
Tolima	R28	24020	24020	79040,2	1087666,7	0
Valle del Cauca	R29	24020	24020	178048,5	7405000	0
Vaupés	R30	24020	24020	3328	0	0
Vichada	R31	26002,2	24486,4	3328	0	583016,2

Table 2
Matrix of distances between regions (km).

	R01	R02	R03	R04	R05	R06	R07	R08	R09	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20	R21	R22	R23	R24	R25	R26	R27	R28	R29	R30	R31
R01	0	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
R02		0	988	716	670	421	206	813	626	565	747	232	442	417	N.A.	809	580	892	838	532	815	584	897	303	264	391	472	416	436	N.A.	1379
R03			0	957	1071	579	1000	1274	363	1307	948	1292	1089	718	N.A.	899	1039	846	1017	614	1558	392	1358	1006	1045	438	1040	926	1186	N.A.	1329
R04				0	114	862	999	1399	1066	1383	301	944	370	1002	N.A.	1394	1163	268	107	1117	1634	676	1482	1088	1047	647	254	1002	1254	N.A.	1964
R05					0	958	861	1495	1163	1212	398	895	281	1099	N.A.	1491	1260	382	221	1214	1463	773	1579	921	877	682	199	1099	1083	N.A.	2032
R06						0	422	696	216	730	726	715	755	141	N.A.	539	461	871	817	262	980	417	780	428	467	282	878	348	609	N.A.	1109
R07							0	661	637	388	863	303	636	293	N.A.	687	381	1008	955	410	638	700	655	97	52	507	666	176	259	N.A.	1257
R08								0	904	267	1263	812	1224	549	N.A.	915	236	1408	1354	638	390	1100	245	526	565	907	1415	446	377	N.A.	1485
R09									0	945	924	930	953	356	N.A.	536	677	1069	1016	252	1196	493	995	644	683	481	1077	564	824	N.A.	967
R10										0	1251	555	991	586	N.A.	953	274	1396	1343	676	246	1086	268	310	340	894	1020	395	141	N.A.	1523
R11											0	974	433	866	N.A.	1258	1027	159	256	981	1497	540	1346	951	911	449	317	866	1118	N.A.	1828
R12												0	670	566	N.A.	933	576	1119	1066	656	805	811	819	292	253	618	700	371	425	N.A.	1503
R13													0	790	N.A.	1183	951	605	444	905	1200	811	1270	659	614	721	122	790	821	N.A.	1752
R14														0	N.A.	400	314	1010	956	123	833	556	633	281	320	426	856	201	462	N.A.	970
R15															0	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
R16																0	690	1411	1357	284	1209	962	1008	657	696	832	1418	577	837	N.A.	1131
R17																	0	1172	1119	402	520	864	320	290	329	671	1180	210	323	N.A.	1249
R18																		0	172	1127	1646	686	1492	1097	1056	595	488	1011	1266	N.A.	1974
R19																			0	1073	1588	632	1438	1043	1003	541	325	958	1208	N.A.	1920
R20																				0	924	578	724	373	412	520	973	293	553	N.A.	852
R21																					0	1332	146	556	585	1140	1266	641	387	N.A.	1768
R22																						0	1181	786	746	195	693	701	953	N.A.	1523
R23																							0	573	602	991	1499	530	404	N.A.	1569
R24																								0	49	601	727	86	179	N.A.	1217
R25																									0	557	682	124	209	N.A.	1256
R26																										0	602	511	763	N.A.	1473
R27																											0	857	887	N.A.	1819
R28																												0	265	N.A.	1137
R29																													0	N.A.	1397
R30																														0	N.A.
R31																															0

Table 3
Material balance coefficients and maximum and minimum bounds for the production technologies.

	Feedstock, products and waste												Production bounds (t of main product per year)	
	FFB	CPO	CPKO	RPO1	RPO2	biodiesel	kernel	cake	biomass1	biomass2	glycerine	EP	Min.	Max.
T1	−6,25	1	0	0	0	0	0181	0	1724	3378	0	0	93,600	187,200
T2	0	0	1	0	0	0	2083	1041	0	0	0	0	93,600	93,600
T3	0	−1,14	0	0	0	1	0	0	0	0	0,32	0	20,000	200,000
T4	0	−24,176	0	1	0	0	0	0	0	0	0	0	93,600	187,200
T5	0	−94,857	0	0	1	0	0	0	0	0	0	0	93,600	187,200
T6	0	0	0	0	0	0	0	0	−7256	0	0	1	60,000	300,000
T7	0	0	0	0	0	0	0	0	0	−14,447	0	1	60,000	300,000

Table 4
Parameters used to calculate the capital and operating costs for different transportation modes. Adapted from Kostin et al. (2018).

	Medium truck	Tanker truck
Average speed (km/h)	60	60
Capacity (t/trip)	25	20
Availability of transportation mode (h/day)	16	16
Cost of transportation mode (USD)	350,000	315,000
Driver wage(USD/h)	4,4	4,4
Fuel consumption (km/L)	2,5	360
Fuel price (USD/L)	0,8	0,8
General expenses (USD/day)	16,3	12,260
Product load/unload time (h/trip)	6	6
Maintenance expenses (USD/km)	0,0976	0,0976

Table 5
Parameters used to evaluate the capital cost for different production technologies. Source: personal comunication.

Technologies	$\alpha^{PL}_{p,r,t}$ (USD)	$\beta^{PL}_{p,r,t}$ (USD· y/t)
T1	40.000.000	145
T2	4.000.000	87
T3	22.000.000	115
T4	2.500.000	43
T5	2.500.000	43
T6	9.500.000	135
T7	9.500.000	135

Table 6
Parameters used to evaluate the capital cost for different storage technologies. Source: personal comunication.

Technologies	$\alpha^{S}_{s,r,t}$ (USD)	$\beta^{S}_{s,r,t}$ (USD· y/t)
S1	160.000	151
S2	1.500.000	180

taken from Fedebicombustibles (2020) show a current configuration of 12 biodiesel production plants in Colombia. In this case, the model raises the possibility of installing 21 plants. The capacity of biodiesel plants is more than four times (4.7) higher than the current capacity.

Table 7 shows the optimal configuration obtained by the model for the scenario CD. The R20 Region (Meta) turns out to have the largest number of industrial establishments in the optimal solution. The percentage of industries installed in region R20 (with respect to the total of industries nationwide) is 28.3%. This region prevails over the others for having the highest production capacity (t/year) of FFB (Table 1). Also, geographically, R20 is close to region R14 (Cundinamarca) (see Table 2), which has a high demand for oil palm products and by-products (Table 1). Regarding other regions in which the installation of plants is important in this scenario, the regions R09 and R19 has the second highest percentage (13.3%) of all installations, while R02 (Antioquia), R11 (Cesar) and R22 (Norte de Santander) present the lowest percentage of plant installation (3.3%). Plants with T6 and T7 technologies that produce electricity from biomass are installed in R05 (Bolívar), R09 (Casanare), R19 (Magdalena), R20 (Meta), R21 (Nariño) and R26 (Santander).

Two technologies stood out for the number of installations in the solution optimal model: T1 and T3. If these two technologies are considered together, installed plants represent 81.7% of the total installed (Table 7). The number of plants that generate electricity from biomass, T6 and T7, represent 16.7%. The amount of plants using T2 technology to produce CPKO, correspond to 3.1%. Since we start from an initial solution in which there are no plants or warehouses installed, the optimal solution suggests the installation of all the plants in the first year of the analyzed period (Table 8).

In Table 9, the levels of demand satisfaction for biodiesel is shown. 100% of the demand is satisfied in all regions, except in R01 (Amazonas), R15 (Guainía), and R30 (Vaupés). The model proposes to install some capacity to generate electricity, at the end of the time horizon (Table 10). These capacities and the demand satisfaction of electricity per region is reported in (Table 10).

5.2. Increasing demand scenario

The optimal number of T1 plants to be installed in the first year, according to the proposed model, is 32. Which is 38% less than the 52 registered in the last census, carried out in 2011 (Fedepalma, 2019). For the production of biodiesel (T3), the model raises the possibility of duplicating the current number of facilities (24). The proposed capacity of biodiesel plants, exceeds in more than six times (6.6) the current capacity. The differences between reality and the results of the model are due to the fact that the existing configuration of the oil palm network and the used technologies were not planned from the beginning with systematic tools from a holistic perspective, unlike the model proposed in this study.

Table 7 shows the optimal configuration obtained by the model for this demand scenario. As in scenario CD, the R20 Region (Meta) results to have the largest number of industrial establishments in the optimal solution. That is, the percentage of plants installed in region R20 is 28.8%. Other regions in which the installation of plants are important are R05 (Bolívar), R09 (Casanare) and R19 (Magdalena), each region representing 12.3% of the total installed plants. Plants with T6 and T7 technologies that produce bio-based electricity are installed in regions R05, R09, R11 (Cesar), R19, R20, R21 and R26.

T1 and T3 technologies prevailed for the number of installations in the optimal solution. If these two technologies are considered together, installed plants represent 75.3% of the total installed, higher than in the scenario CD (Table 7). The number of plants that generate electricity from biomass, T6 and T7, represent

Table 7
Number of technologies installed in different regions for the two scenarios considered.

	T1		T2		T3		T6		T7		Total ID	Total CD
Region	ID	CD	ID	CD	ID	CD	ID	CD	ID	CD		
R02	1	1	0	0	1	1	0	0	0	0	2	2
R05	4	3	0	0	3	3	1	0	1	1	9	7
R09	4	4	0	0	3	3	1	1	1	0	9	8
R11	2	1	0	0	2	1	1	0	0	0	5	2
R19	4	4	1	0	3	2	1	1	1	1	10	8
R20	9	8	1	1	7	6	2	1	2	1	21	17
R21	3	3	1	0	2	2	1	1	1	1	8	7
R22	2	1	0	0	1	1	0	0	0	0	3	2
R26	3	3	0	0	2	2	1	1	1	1	7	7
Total	32	28	3	1	24	21	8	5	7	5	74	60

Table 8
Number of technologies installed in different years and different scenarios.

	year01		year02		year03		year04		year05	
Technology	ID	CD	ID	CD	ID	CD	ID	CD	ID	CD
T1	32	28	0	0	0	0	0	0	0	0
T2	3	1	0	0	0	0	0	0	0	0
T3	21	21	3	0	0	0	0	0	0	0
T6	8	5	0	0	0	0	0	0	0	0
T7	7	5	0	0	0	0	0	0	0	0
Total	71	60	3	0	0	0	0	0	0	0

Table 10
Electricity generation capacity and demand satisfaction in both demand scena-rios.

Region (state)	Associated region	Capacity MWy	ID	CD
Antioquia	R02	66669,4	1.1%	1.4%
Bolívar	R05	302371	7.7%	8%
Casanare	R09	317610,2	11.6%	14.8%
Cesar	R11	129698,4	4.4%	3.2%
Magdalena	R19	323421,2	7.7%	9.2%
Meta	R20	838457,6	10%	11.2%
Nariño	R21	208309,7	25.2%	30.3%
Norte de Santander	R22	129698,4	4.4%	3.7%
Santander	R26	259396,8	7.5%	10.9%

20.5%. The amount of plants using T2 technology to produce CPKO, correspond to 4.1%. The model decides to install plants of T2 technology in regions R19 (Magdalena), R20 (Meta) and R21 (Nariño). The optimal geolocation of CPKO producing plants, in regions R19 and R21, is due to the fact that these regions have port facilities and are close to the production centers. Regarding CPKO production in R20, the model chooses this region for its production capacity (Table 1), in addition to the proximity (Table 2) to a region of very high demand such as R14 (Table 1).

The optimal solution suggests the installation of most of the plants 96% in the first year of the analyzed period. remaining plants are installed the next years (Table 8). Plants are installed, from the second year on, in R05 (Bolívar), R19 (Magdalena) and R20 (Meta) where it is proposed to install new T3 plants in the second year.

With respect to storage, in both scenarios of demand, storage facilities are installed for liquid products (CPO, CPKO, and biodiesel) in 28 regions. Warehouses are not installed in R01 regions (Amazonas), R15 (Guainía), and R30 (Vaupés), due to low demand for these products in these regions. All investments in warehouses are made in the first year. The demand satisfaction levels for biodiesel are shown in Table 9. For scenario ID, a general average demand satisfaction: for all regions of 78.6% is verified, with regions R08 (Caquetá), R12 (Chocó), and R31 (Vichada) being the ones with the lowest satisfaction in this scenario with 31%, 27.1%, and 20.6%, respectively.

Biomass1 and biomass2 produced in different regions, are fully consumed to produce electrical energy, in both scenarios. The electricity supply network that is generated from the residual biomass of the oil palm industry can be seen in Fig. 5. The regions with the largest oil palm crops such as R02 (Antioquia), R05 (Bolívar), R11 (Cesar), R19 (Magdalena), R20 (Meta), R21 (Nariño), R22 (Norte de Santander), and R26 (Santander), provide a surplus of electrical energy to cover part of the demand, with T6 and T7-type plants installed in each of these regions.

The capacity to generate electricity in scenario ID can be seen in Table 10. The demand satisfaction of the three regions that contribute the most is: in R09, 11.6%, in R20, 10% and in R21, 25.2%. In all cases, results show an enrichment, in renewable energy, of the Colombian energy matrix.

5.3. Sensitivity analysis

The difference in the results between the scenarios is an indication of the sensitivity of the optimal configuration to the demand pattern that is being implemented. On the other hand, two of the seven technologies are not used (T4 and T5), which indicates that these technologies are not efficient enough for the model. A sensitivity analysis was carried out on the prices of refined products RPO1 and RPO2 (produced by T4 and T5) to encourage their production, obtaining that the model decides to install the first T4 type plant (in the R20 region, during the first year), when the increase is 43% above the original price. In other tests, where the installation of at least one T4 plant and at least one T5 one was

Table 9
Biodiesel demand satisfaction in different demand scenarios.

	R02	R03	R04	R05	R06	R07	R08	R09	R10	R11	R12	R13	R14	R16
ID	92,6%	86,1%	97,6%	99,4%	97,7%	75,8%	31%	100%	16,2%	97,7%	27,1%	50,3%	97,7%	93,1%
CD	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	R17	R18	R19	R20	R21	R22	R23	R24	R25	R26	R27	R28	R29	R31
ID	86,1%	93,1%	100%	100%	100%	97,7%	65,7%	93,1%	57,7%	100%	86,1%	93,1%	44,7%	20,6%
CD	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

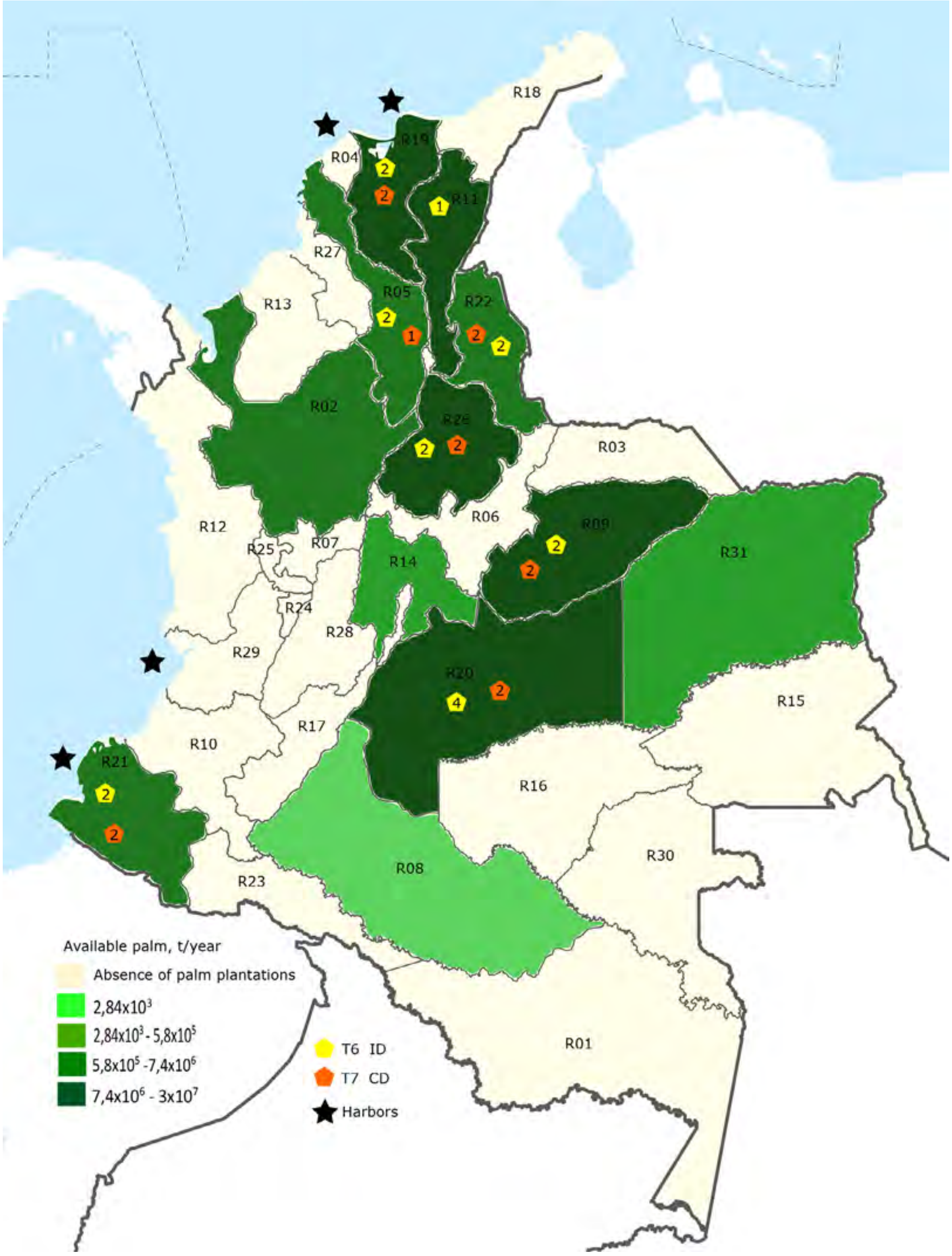

Fig. 5. Optimal configuration of the electrical network. ID: Increasing Demand, CD: Constant Demand.

required, the model finds feasible solutions in which it registers installations of both types of plants in all regions for both demand scenarios. This latest requirement would model the implementation of a protection policy for these products (RPO1 and RPO2) by the national administration.

In the fixed time horizon (5 years), the operating costs FOC_t and TOC_t show important differences in the two demand scenarios. In the case of factories and warehouses (FOC_t), the scenario ID shows values of this cost always above the case of CD, with an average difference in costs of USD 1.93×10^8 for the scenario CD (see Fig. 6). In the case of transportation (TOC_t) (see Fig. 7), there is no difference between ID and CD in the first two years. From the third year on, transportation cost for the scenario ID starts to decrease, moving away from the cost of the scenario CD. The decrease observed in transportation costs despite the increasing demand of the ID scenario is due to the reduction in distribution channels from the third year in this scenario, causing a decrease of the demand satisfaction in various regions of the country (see Table 9), and consequently, decreasing the costs of distributing products to those markets.

Capital investment in production plants, warehouses, and transportation (see Fig. 8) shows a greater value in the scenario ID. Operating costs of plants, warehouses, and transportation (see Fig. 9) also present a higher value for the ID scenario, yet the transporting cost is the one with the lowest relative difference between scenarios (16%).

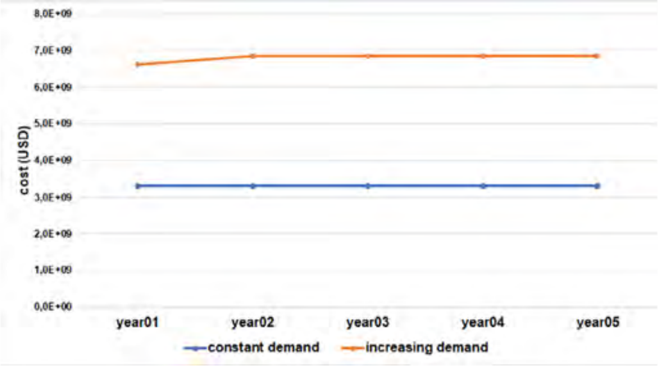

Fig. 6. Facility operating cost.

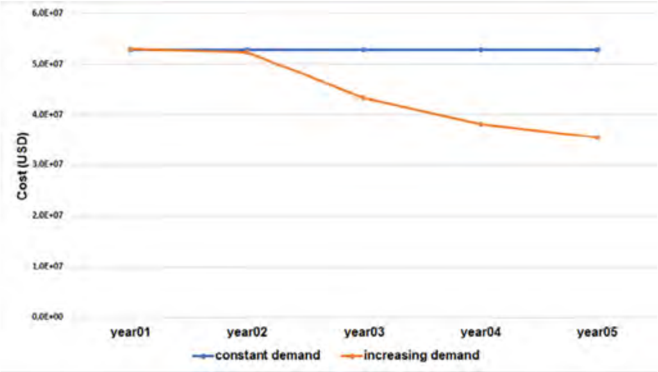

Fig. 7. Transportation operating cost.

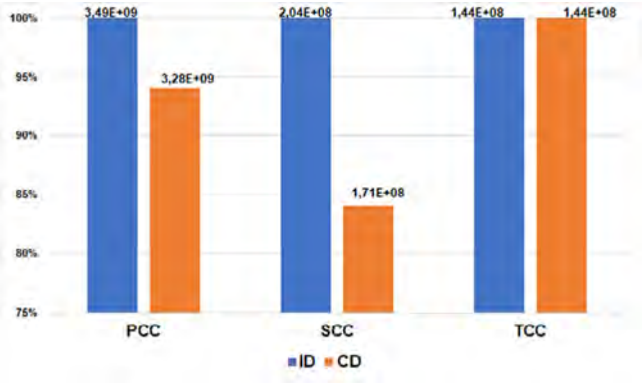

Fig. 8. Facility capital total cost.

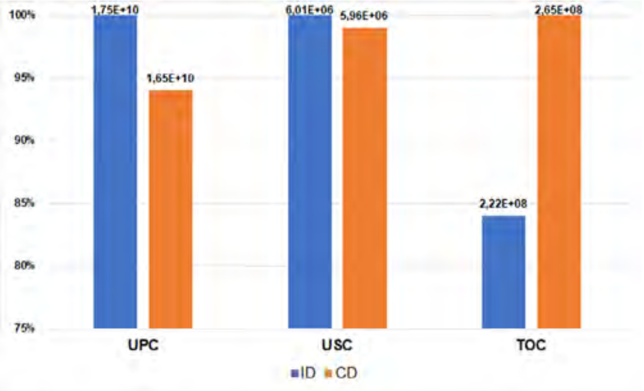

Fig. 9. Facility operating total cost and transportation operating total cost.

6. Conclusions

The present work studied the design and optimal planning of the oil palm SC, including the possibility of producing energy from the biomass generated around it. The optimization problem is solved using a MILP formulation, whose objective function is the maximization of the NPV of the entire SC, along a defined time horizon. The developed model includes seven different production technologies, two types of warehouses, two types of transport modes, and eight export destinations.

Specific data from the palm SC in Colombia was used to develop the model. It serves as a quantitative tool for decision making in the area of strategic design and optimum planning of the industrialization of biomass SC in general, and the oil palm SC in particular. The obtained solution shows a more rational distribution of the productive units, with respect to the Colombian reality. There is currently no strategic planning to encourage the installation of industrial plants in locations that would allow for greater competitivity in the international markets, in addition to improving the development of other regions, increasing jobs and social welfare.

The results show that the network is much more profitable if they include various products, such as CPO, CPKO, biodiesel, and electrical energy than if it only produces biodiesel and palm oil. For future research, it is considered important to complement the economic study with an environmental study of this SC, adding also considerations of parametric uncertainty.

Declaration of Competing Interest

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

CRediT authorship contribution statement

Darwin Peña González: Conceptualization, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft. **Daniel Cortés Borda:** Conceptualization, Writing - original draft, Writing - review & editing, Supervision. **Fernando D. Mele:** Methodology, Software, Validation, Formal analysis, Investigation, Writing - original draft, Writing - review & editing, Visualization. **Agustín Barrios Sarmiento:** Supervision, Project administration. **Mildred Domínguez Santiago:** Supervision, Project administration.

Acknowledgements

The authors are grateful for the support of the Government of Magdalena, the project of scholarships General System of Regalías (SGR) doctorate Nacional Colombia [Not. 672], the Universidad del Norte (Colombia) and the CYKLOS research group of the National University of Tucumán (Argentina).

Supplementary material

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.compchemeng.2020.107208.

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Chapter 4

Preprint submitted to Computers & Chemical Engineering

The results and discussion of the case study submitted as a preprint to the Computers & Chemical Engineering Journal on September 24th, 2020, are presented in this chapter. In this sense, this section reports the results obtained by considering different parameters to those used in the article presented in chapter 3, including the time horizon (10 years in this case), the optimality gap, which was developed with a value of 10%. When these parameters were used, different results in terms of the production of biodiesel and electricity, the expansion of the capacity of both production plants and storehouses, the network, the material flow, and the means of transportation to be implemented in each region of the country were obtained, which in turn allowed for a better analysis of the strategic planning of the palm oil SC in Colombia.

Results and Discussion

The optimal configuration achieved by the proposed model —for both scenarios— was compared with the current configuration published by different Colombian organizations: SISPA by Fedepalma (2019), the Colombian Ministry of Energy (MME-UPME, 2019), the National Federation of Biofuels of Colombia (Fedebicombustibles, 2020) and the National Agency for Infrastructure (ANI, 2020). The optimal number of T1 plants to be installed in the first year, according to the proposed model, is 37 for scenario ID. Which is 30% less than the 52 registered in the last census, carried out in 2011 (Fedepalma, 2019). For the scenario CD, the model proposes fewer plants of T1 technology (30). For the production of biodiesel (T3), data taken from Fedebicombustibles (2020) show a current configuration of 12 biodiesel production plants in Colombia. In this case, the model raises the possibility of installing more than double (26) for the scenario ID, and 22 for the scenario CD. The capacity of biodiesel plants, in the scenario CD, is more than four times (4.7) higher than the real capacity, while in the scenario ID, it exceeds it more than six times (6.6). The differences between reality and the results of the model are due to the fact that the existing configuration of the oil palm network and the used technologies were not planned from the beginning with systematic tools from a holistic perspective, unlike the model proposed in this study.

Table (7) shows the optimal configuration obtained by the model for the two proposed demand scenarios, ID and CD. The R20 Region (Meta) turns out to have the largest number of industrial establishments in the optimal solution. That is, the percentage of industries installed in region R20 (with respect to the total of industries nationwide) is 29.2% for ID and 24.6% for CD. This region prevails over the others for having the highest production capacity (t/year) of FFB (Table (1)). Also, geographically, there is proximity (see Table (2)) to department R14 (Cundinamarca), which has a high demand for oil palm products and by-products (Table 1).

Other regions in which the installation of plants is important, in the scenario ID, are R05 (Bolívar), R09 (Casanare), and R19 (Magdalena), which represent 10.4%, 11.5% and 11.5% of the total installed plants, respectively. Regarding the solution of the scenario CD, the region R05 presents the lowest percentage of plant installation (1.4%), while R19 has the highest percentage (25.7%) of all installations. In the scenario ID, plants with T6 and T7 technologies that produce electricity from biomass are installed: regions R02 (Antioquia), R05 (Bolívar), R09 (Casanare), R11 (Cesar), R19 (Magdalena), R20 (Meta), R21 (Nariño), R22 (Norte de Santander), and R26 (Santander). Instead, in scenario CD, no plants with these technologies are installed in the R11 region. The difference in the results between the scenarios is an indication of the sensitivity of the optimal configuration to the demand pattern that is being implemented. On the other hand, two of the seven technologies are not used (T4 and T5), which indicates that these technologies are not efficient enough for the model. A sensitivity analysis was carried out on the prices of refined products RPO1 and RPO2 (produced by T4 and T5) to encourage their production, obtaining that the model decides to install the first T4 type plant (in the R20 region, during the first year), when the increase is 43% above the original price. In other tests, where the installation of at least one T4 plant and at least one T5 one was required, the model finds feasible solutions in which it registers installations of both types of plants in all regions for both demand scenarios. This latest requirement would model the implementation of a protection policy for these products (RPO1 and RPO2) by the national administration.

Table 7: Number of technologies installed in different regions for the two scenarios considered

	T1		T2		T3		T6		T7		Total	Total
Region	ID	CD	ID	CD	ID	CD	ID	CD	ID	CD	ID	CD
R02	2	2	0	0	1	1	1	1	1	1	5	5
R05	5	0	0	0	3	0	1	0	1	1	10	1
R06	0	0	0	0	0	1	0	0	0	0	0	1
R09	5	2	0	0	4	1	1	1	1	1	11	5
R11	2	0	0	0	2	0	1	0	1	0	6	0
R19	5	8	1	1	3	6	1	2	1	2	11	19
R20	13	7	1	1	10	5	2	2	2	2	28	17
R21	4	4	1	1	2	2	1	1	1	1	9	9
R22	2	2	0	0	2	2	1	1	1	1	6	6
R26	4	5	0	0	3	4	1	1	1	1	9	11
R27	0	0	0	0	1	0	0	0	0	0	1	0
Total	42	30	3	3	31	22	10	9	10	10	96	74

Two technologies stood out for the number of installations in the solution optimal model: T1 and T3. If these two technologies are considered together, installed plants represent 76% of the total installed in the scenario ID and 70.3% in the scenario CD (Table 7). The number of plants that generate electricity from biomass, T6 and T7, represent 20.8% for the ID scenario and 27.5% in the scenario CD. The amount of plants using T2 technology to produce CPKO, correspond to 3.13% for the ID and 4.3% for the CD. The model decides to install plants of the T2 technology in the R19 (Magdalena), R20 (Meta) and R21 (Nariño) regions. The optimal geolocation of CPKO producing plants, both in region R19, as in R21, is due to the fact that the model decides to install said plants in port areas close to the production centers. Regarding CPKO production in R20, the model chooses this region for its capacity of production (Table 1), in addition to the proximity (Table (2)) to a region of very high demand such as R14 (Table 1).

Since we start from an initial solution in which there are no plants or warehouses installed, the optimal solution suggests the installation of most of the plants in the first year of the analyzed period. As expected, in scenario ID, the installation of plants is 85.4%, with the rest installed in successive years. In the scenario CD, practically all the plants are installed in the first year (97.3%) (Table 8). In the scenario ID, plants are installed, from the second year on, in R02 (Antioquia), where it is proposed to install new T1, T3, and T7 plants in the second year; R27 (Sucre), where new T3 plants are installed in the second year; and R26 (Santander), where T7 plants are installed in the second year and T6 plants in the fourth year.

With respect to storage, in both scenarios of demand, storage facilities are installed for liquid products (CPO, CPKO, and biodiesel) in 28 regions. Warehouses are not installed in R01 regions (Amazonas), R15 (Guainía), and R30 (Vaupés), due to low demand for these products in these regions. All investments in warehouses are made in the first year.

Table 8: Number of technologies installed in different years and different scenarios

	year01		year02		year03		year04		year05		year06		year07		year08		year09		year10	
Tecnología	ID	CD	ID	CD	ID	CD	ID	CD	ID	CD	ID	CD	ID	CD	ID	CD	ID	CD	ID	CD
T1	37	30	4	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T2	3	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
T3	26	22	4	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0
T6	8	8	0	0	0	0	2	0	0	1	0	0	0	0	0	0	0	0	0	0
T7	8	9	2	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total	82	72	10	0	1	1	3	0	0	1	0	0	0	0	0	0	0	0	0	0

In Table 9, you can see the levels of satisfaction of the demand for biodiesel for both scenarios. For the scenario CD, 100% of the demand is satisfied in all regions, except in R01 (Amazonas), R15 (Guainía), and R30 (Vaupés). For ID, a general average demand satisfaction for all regions of 78% is verified, with regions R08 (Caquetá), R23 (Putumayo), and R31 (Vichada) being the ones with the lowest satisfaction in this scenario with 37.9%, 37.3%, and 20.6%, respectively.

Table 9: Biodiesel demand satisfaction in different demand scenarios

	R02	R03	R04	R05	R06	R07	R08	R09	R10	R11	R12	R13	R14	R16
ID	92,4%	91%	92,2%	99,1%	97,3%	81,3%	37,9%	99,1%	30,5%	99,1%	39,2%	38,8%	99,1%	94,6%
CD	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%
	R17	R18	R19	R20	R21	R22	R23	R24	R25	R26	R27	R28	R29	R31
ID	91%	78,1%	100%	100%	99,4%	100%	37,3%	91%	69,6%	100%	77,3%	94,6%	55,4%	20,6%
CD	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%	100%

Biomass1 and biomass2 produced in different regions, are consumed, in their entirety, to produce electrical energy, in both scenarios. The electricity supply network that is generated from the residual biomass of the oil palm industry can be seen in Figure 5. The regions with the largest oil palm crops such as: R02 (Antioquia), R09 (Casanare), R11 (Cesar), R19 (Magdalena), R20 (Meta), R21 (Nariño), R22 (Norte de Santander), and R26 (Santander) provide a surplus of electrical energy to cover part of the demand, with T6 and T7-type plants installed in each of these regions.

For both scenarios, the model proposes a capacity to generate electricity, at the end of the time horizon, which can be seen in Table 10. In scenario ID, the satisfaction of the demand of the three regions that contribute the most is: in R09, 12.3%, in R20, 12.2% and in R21, 20.9%, while, in the scenario CD, the satisfaction of the demand is: in R09, 7.7%, in R19, 20.5%, and in R21, 30.3% (Table 10). In all cases, results show an enrichment, in renewable energy, of the Colombian energy matrix.

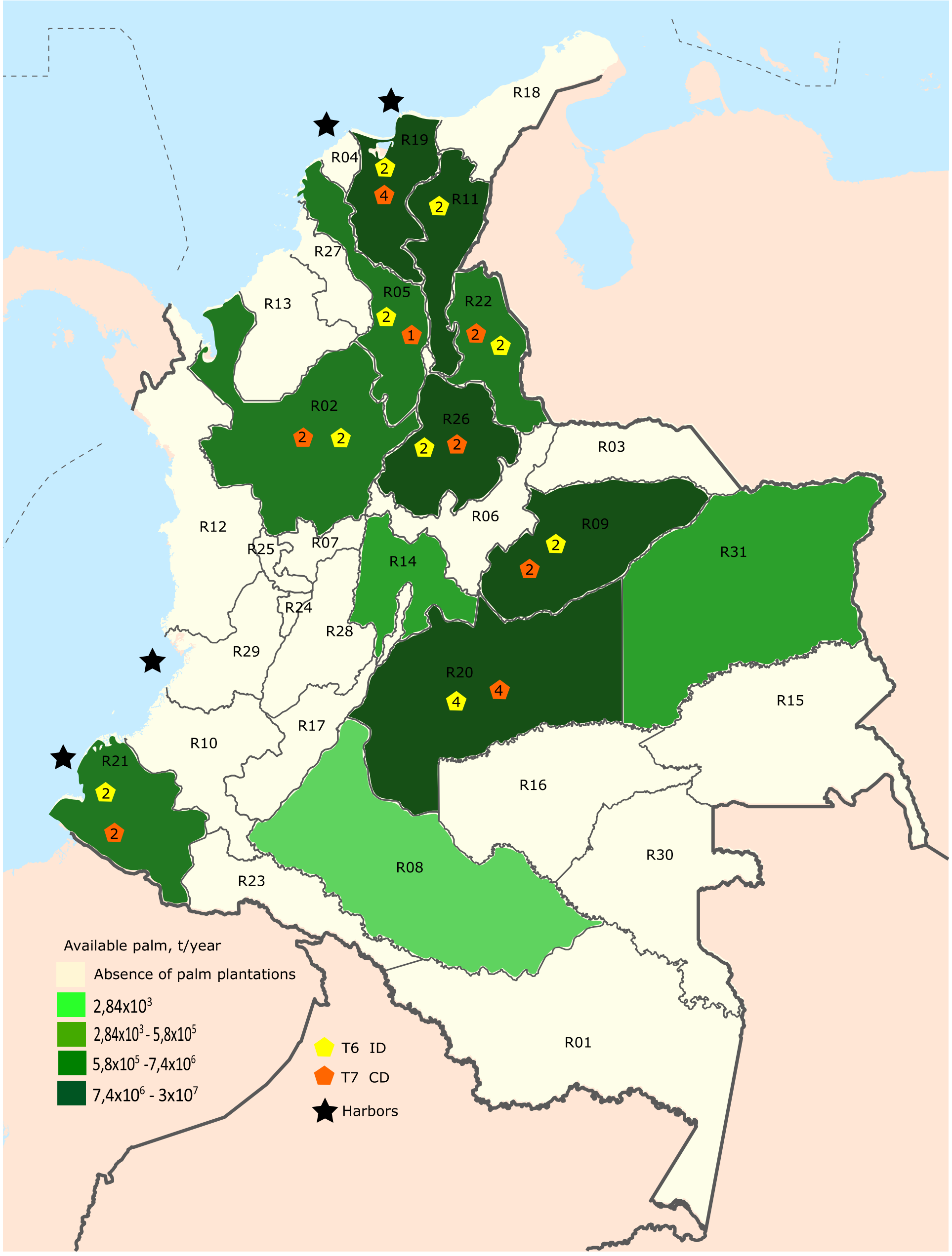

Figure 5: Optimal configuration of the electrical network. ID: Increasing Demand, CD: Constant Demand

Table 10: Electricity generation capacity and demand satisfaction in both demand scenarios

Region (state)	Associated region	Capacity MWy	ID	CD
Antioquia	R02	66669,4	0,6%	1,4%
Bolívar	R05	302371	8,1%	0%
Casanare	R09	317610,2	12,3%	7,7%
Cesar	R11	129698,4	2,8%	0%
Magdalena	R19	323421,2	8,5%	20,5%
Meta	R20	838457,6	12,2%	9,4%
Nariño	R21	208309,7	20,9%	30,3%
Norte de Santander	R22	129698,4	5,3%	7,7%
Santander	R26	259396,8	8,5%	19,3%

In the fixed time horizon (10 years), the operating costs FOC_t and TOC_t show important differences in the two demand scenarios. In the case of factories and warehouses (FOC_t), the scenario ID shows an increasing behavior, always above the case of CD, stabilizing towards the end of the time horizon, with an average difference in costs of USD 1.94×10^9 for the scenario CD (see Figure 6). In the case of transportation (TOC_t) (see Figure 7), there is an average cost difference in the first seven years of about USD 1.34×10^7, between ID and CD, while in the last three years, the cost difference is higher for CD (average of USD 4.8×10^6). The decrease observed in transport costs despite the increasing demand of the ID scenario is due to the reduction in distribution channels from the fourth year in this scenario, causing the satisfaction of the demand to decrease in various regions of the country (see Table 9), and consequently, decreasing the costs of distributing products to those markets.

Capital investment in production plants, warehouses, and transportation (see Figure 8), shows a greater investment in the scenario ID. Besides operating costs of plants, warehouses, and transportation (see Figure 9) present a higher value for the ID scenario, with the storage operating cost being the one with the lowest percentage difference between both scenarios (5%).

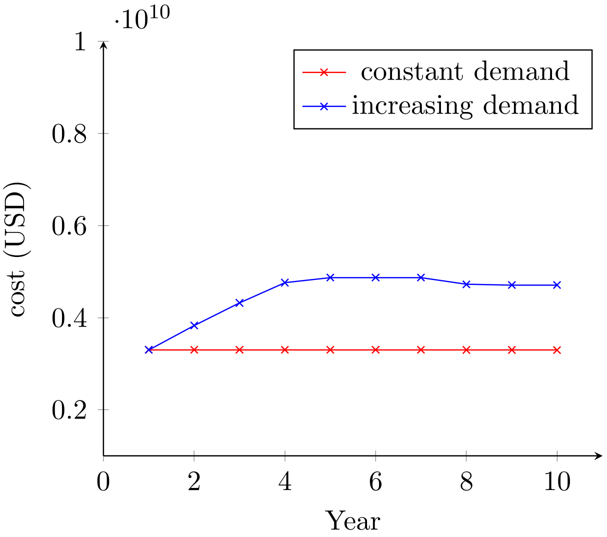

Figure 6: Facility operating cost

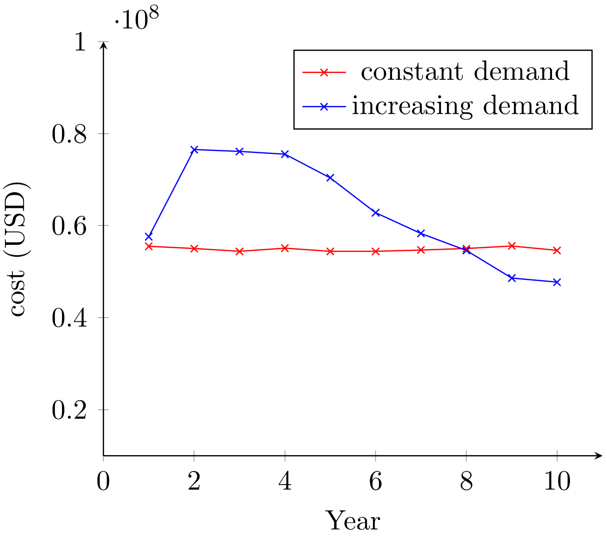

Figure 7: Transportation operating cost

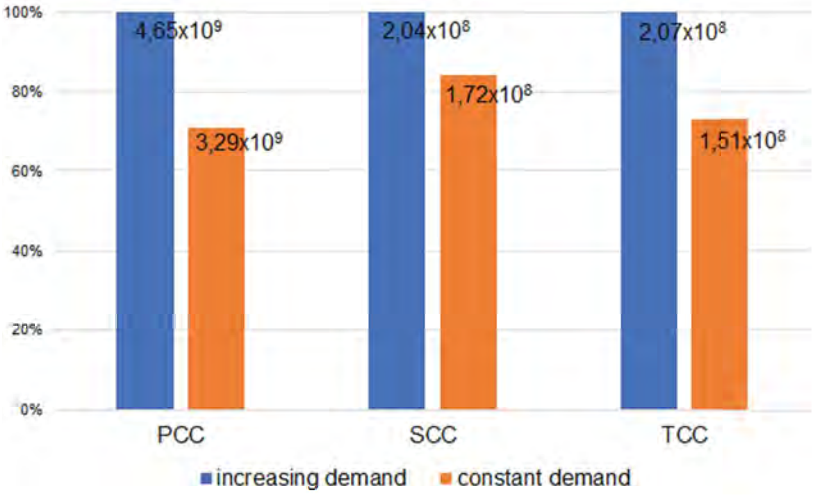

Figure 8: Facility capital total cost

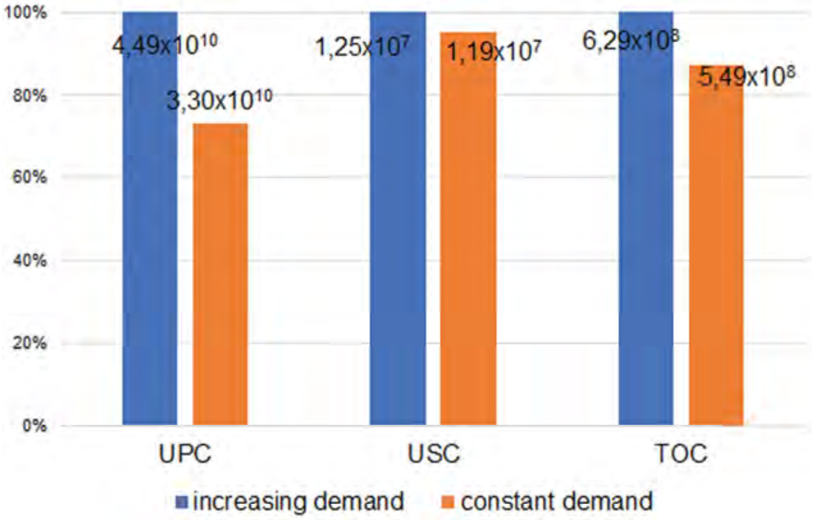

Figure 9: Facility operating total cost and transportation operating total cost

Chapter 5

A multiobjective approach for the design and planning of more sustainable oil palm supply chains

This article, which was submitted for possible publication to the Journal of Cleaner Production on June 28th, 2021, is presented in this chapter. It describes an optimization framework for achieving a sustainable design of the palm oil SC in Colombia. For this purpose, a MILP model aimed at optimizing this SC taking into account both its environmental and economic aspects was developed. Results are presented in a Pareto front that shows the balance between economic and environmental objectives. The environmental impact is measured using eco-points derived from the LCA methodology. Decreasing the profitability of the SC will reduce its environmental impact. This model shows that the environmental impact of the SC can be significantly decreased by adjusting its operation conditions and topology. It is worth noting that this dissertation used the LCA data obtained by Lucas Machin Ferrero, from Process Engineering and Industrial Management Department -Exact Sciences and Technology School-Universidad Nacional de Tucumán, Argentina.

A multiobjective approach for the design and planning of more sustainable oil palm supply chains

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Abstract

The palm industry is at the center of global attention due to its controversial socio-environmental implications. This article presents a mixed integer multiobjective linear program (MILP) that seeks to optimize the supply chain (SC) of oil palm, precisely considering the environmental aspects together with the economic ones. Decision variables of the model are the location of the storage and production facilities, their expansion possibilities, and the flows of feedstock and various products involved in the SC. The features of the approach are illustrated through a real-scaled case study in Colombia. It results in a Pareto front that shows the trade-off between economic and environmental issues. The latter is measured through different scores derived from a life cycle assessment (LCA)-based procedure. This optimization model will help stakeholders to get a better insight and make decisions towards a more sustainable palm sector.

Keywords: Optimization; integer programming; sustainability; life cycle assessment; biodiesel; bioenergy

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1. Introduction

The Oil palm (*Elaeis guineensis*) has a huge potential in the vegetal oil industry due to the big advantages compared to other kind of oil production, such advantages might be productivity, ease with the planting, preservation and management of the harvest, and adaptability to dormant grasslands, scrublands and felled secondary forests (Batugal, 2013; Barcelos et al., 2015). This crop is native to west and southwest Africa, but is it now naturalized in Madagascar, Sri Lanka, Southeast Asian, Central America and Caribbean Islands, and also in the Pacific and Indian Oceans.

Palm oil is extracted from both the pulp of the fruit (palm oil, CPO) and the kernel (palm kernel oil, CPKO) and it is mainly used in foods and for soap manufacture. The high oil palm plantation, as high as 7,250 liters per hectare per year (Woittiez et al., 2017), has made it common its use in the commercial food industry all around the world due to its lower pricing, the oxidative stability of the refined product and high levels of natural antioxidants.

In 1995, Malaysia was the world's biggest exporter of palm oil, with a 51% plantation in all over the world, but since 2007, Indonesia has taken over this position by supplying about 50% of palm oil worldwide. Nowadays, Colombia ranks fourth with a 2% of the world provision, preceded by Indonesia (58%), Malaysia (26%) y Thailand (4%)(USDA, 2021a). Worldwide palm oil production is currently 75.5 million of tons (2020/2021) (USDA, 2021b).

The increase in palm oil demand in the past years is due to its use as biofuel. But opposite to its production advantages, the palm supply chain (SC) —production, industrialization, distribution and commercialization of the products— causes controversy because of the social and environmental implications, among which is the endless discussion food against fuels.

From the social view, farming the oil palm is a very profitable activity, and an important source of employment that makes it possible the inclusion of little landowners and produces improvements to housing infrastructure in the areas where it has influences. However, there are some cases in which Oil palm has taken possession of lands causing social conflicts that include illegal work and bad job conditions (Brandão et al., 2019; Ayompe et al., 2021;

Castellanos-Navarrete et al., 2021; Teng et al., 2020; Acosta and Curt, 2019).

On the environmental side, the loss of biodiversity is one of the most serious negative effects of the crops due to, for instance, the deforestation of large areas of jungle to make way for planting and to burning outdoor the plantation waste. Added to this impact is the release in the atmosphere of carbon stored in peat bogs earned for cultivation, respiratory effects in humans and ecotoxicity (Reijnders and Huijbregts, 2008; Schmidt, 2010; Zulkifli et al., 2009; Abdul-Manan, 2017). The environmental effects come not only from deforestation but also from other stages of the palm tree activity life cycle; from farming (for instance, the use of fertilizers and fossil fuels in machinery) until refining the products (release of milling plant effluents into the environment, POME) (Schmidt, 2007; Bessou et al., 2012, 2014; Saswattecha et al., 2015).

It has been affirmed that during its life cycle a specific volume of palm biodiesel releases more carbon than the same amount of fossil fuel volume (AZoCleantech, 2020). Therefore, there is an upcoming protection effort trying to promote a sustainable palm oil production through Roundtable about Sustainable Palm Oil (Cattau et al., 2016; Webber, 2017; Noor et al., 2017) and about the financing of carbon credit projects through the Clean Development Mechanism (Seeberg-Elverfeldt, 2010; Twenergy, 2019) starting, mainly, from taking advantage of using the wastes of this activity (Hambali, 2010). It is known that, per each ton of palm oil, a farmer gets around six tons of agricultural wastes, a ton of palm trunks, five tons of empty fruit bunches, a ton of pressed fiber (from fruit mesocarp), half a ton of endocarp, 250 kg of almond cake and among 0,35 to one tons of POME (Van Dam, 2016).

It has then been proposed to transform waste biomass into renewable electricity and heat (by incineration and cogeneration) cellulosic ethanol, biohydrogen and bioplastics (White, 2010; EC, 2017; Peña González et al., 2021). Besides, an anaerobic treatment of POME can be put in practice to generate biogas (methane), and then electricity (Flórez, 2013; Chaikitkaew et al., 2015). Another alternative for biomass is recycling its waste to make medium density fiber boards and light furniture (Suhaily et al., 2012). By following these strategies, it is expected to improve both the energy balance and the balance of greenhouse gas (GHG) of palm biodiesel.

Currently, the Life Cycle Analysis (LCA) has become in one of the most appropriate tools to measure the environmental effects associated with these complex systems that make it possible to identify the hot spots along the SC. There is a vast number of articles that study from an LCA approach the environmental performance of palm tree biodiesel, such as Wahyono et al. (2020). Hasibuan et al. (2018) and Siregar et al. (2020) in Indonesia; Sampattagul et al. (2011) in Thailand; Maharjan et al. (2017) in Taiwan, and Gómez et al. (2014) and Castanheira and Freire (2017) in Colombia.

Some articles are only focused on the agricultural stage of palm fruit production (Hansen, 2007; Reijnders and Huijbregts, 2008; Schmidt, 2010; Zulkifli et al., 2009; Abdul-Manan, 2017). These studies cover up a great number of impact categories such as abiotic depletion potential, acidification, eutrophication, global warming, human toxicity among others, with special profusion in the evaluation of GHG (Choo et al., 2011; Kaewmai et al., 2012; Bessou et al., 2012, 2014; Lee et al., 2014)

In Colombia (Queiroz et al., 2012) analyze the palm oil and biosdiesel production through LCA. For each productive phase, it is considered the inputs of materials and energy, and the energetic content of products and co-products.

On the other hand, Rivera-Méndez et al. (2017) present integrated strategies which have different effects on the carbon balance with the purpose of increasing the eco-efficiency of palm oil. Bautista et al. (2019) develop and apply a system dynamics model to evaluate the sustainability of biodiesel production. For Ramirez-Contreras et al. (2020), Colombia has the potential to produce sustainable biological-based products from palm oil, however, national GHG emissions have not yet been reported by this sector. Their study estimates GHG emissions, a net energy index and the economic performance, showing that for an optimized production chain, resource and operating expenses decrease by approximately 20%.

This work sets out an optimization approach for the sustainable design of the SC of palm oil in Colombia which, as far as the authors know, has not been integrated into a model that involves the economical aspect and environmental impact generated by the SC of the national palm. A MILP multiobjective optimization model is now being developed, this integrates oil extraction and refining processes, biodiesel production and electrical energy (EP) cogeneration, while the environmental impact is evaluated through the LCA. The estimated SC includes the FFB cultivation, transportation, processing the production of CPO, CPKO, olein, stearin, biodiesel, EP, and exports. This model allows to determine the number, location and production plant and warehouse capacity that need to be installed in every region in which the study of the geographical field has been divided, as well as the connections and ways of transportation that must be established in the network and the raw material flows, products and by-products.

On the planning outlook and for a determine price estimate, it is stipulated the availability of raw material, the demand, and a policy of expansion of capacity of the facilities. Solving this optimization problem or even its modifications might allow a strategic orientation on the distribution of resources and will offer guidelines to address the sustainability of the sector towards the optimum.

The article is structured as follows: Section 2 presents the problem statement; Section 3 shows application of LCA to the oil palm SC; Section 4 introduces the mathematical model; Section 5 describes the case study as developed for the reality of Colombia, but adaptable for other geographic contexts. The results of the case study are discussed in Section 6. Finally, the conclusions of the study and possible future research directions are offered in Section 7.

2. Problem Statement

The structure of the oil palm SC studied in this article is presented in Figure 1. It includes the palm plantations, production and storage facilities, and final markets for the different products, with the corresponding distribution channels. The design problem of this SC can be formally stated as follows. Given are a fixed time horizon; prices and demand forecast for products; unit costs of production, storage and transportation of materials; tax rates; capacities of plants, warehouses and transportation channels; capital investment limits and environmental data (emissions and characterization factors associated with the operation of the network). An integer mixed linear programming model (MILP) is proposed with the objective of determining the configuration of the oil palm SC, and the associated planning decisions that maximize profitability and minimize the environmental impact along the time horizon. Decisions to be made include the number, location, and capacity of the production plants and warehouses that will be installed; their capacity expansion policy; the transportation links and modes; and the flow of raw material, intermediates, final products and waste.

The geographical scope of the study has been divided in different regions. Each region has a known palm production capacity for each time interval of the planning horizon.

3. Environmental impact assessment: application of LCA to the oil palm SC

In this work, the palm oil SC is designed by considering the economic and environmental performance simultaneously. The environmental performance is measured through the application of the LCA phases: goal and scope definition, inventory analysis, and impact assessment (ISO14040, 2006). The remaining phase, LCA interpretation, is performed in our case by incorporating LCA-based metrics in the optimization model.

Goal and Scope Definition. In this phase, we define the system boundaries, allocation methods, and impact categories, among other parameters of the LCA study, which is restricted to the domain of the palm oil SC. The scope is “from cradle to gate”, encompassing all the activities of the network, from the palm growing (agricultural stage) to the delivery of the products to markets.

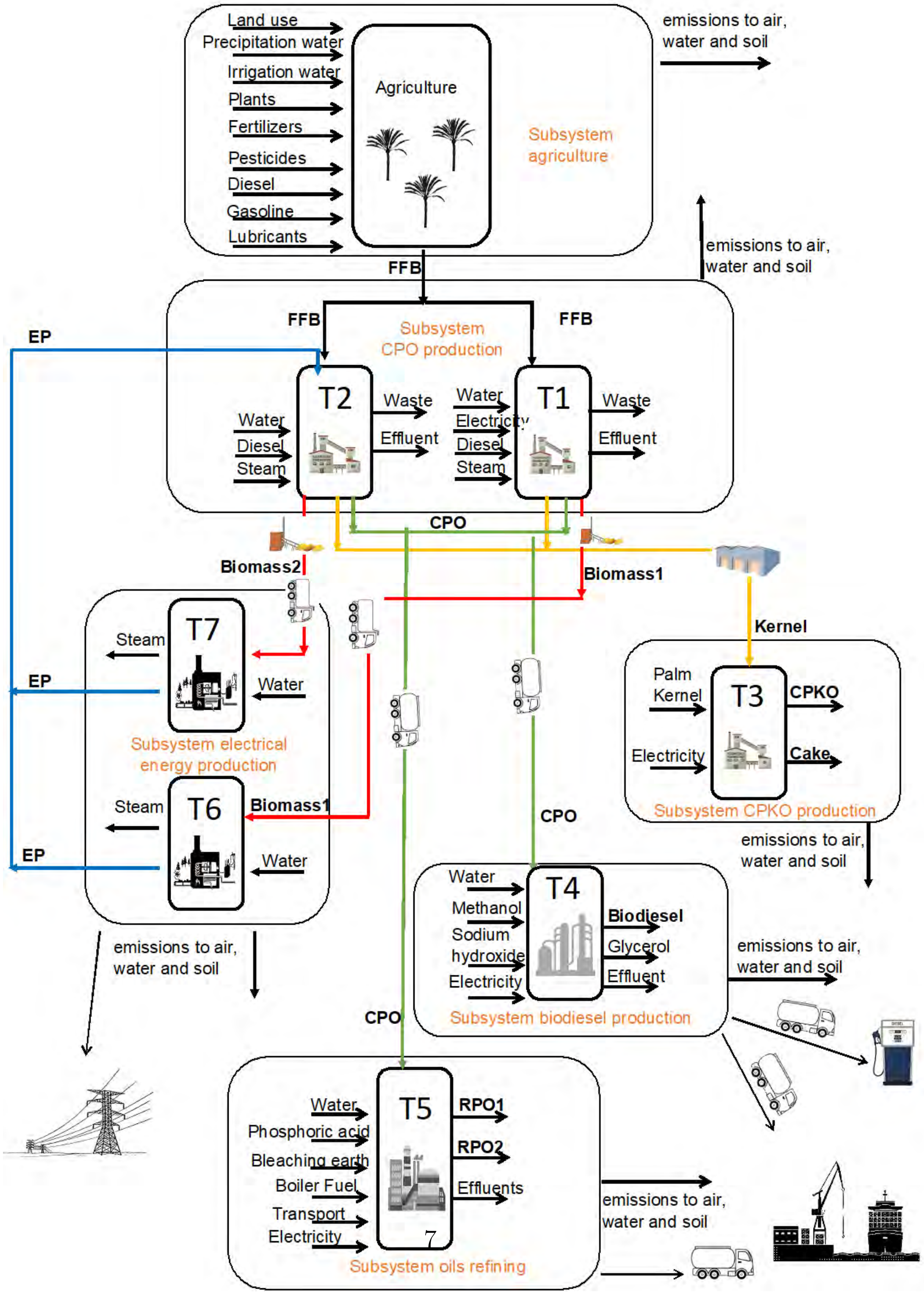


Figure 1: Processes considered within the system boundaries of the LCA study

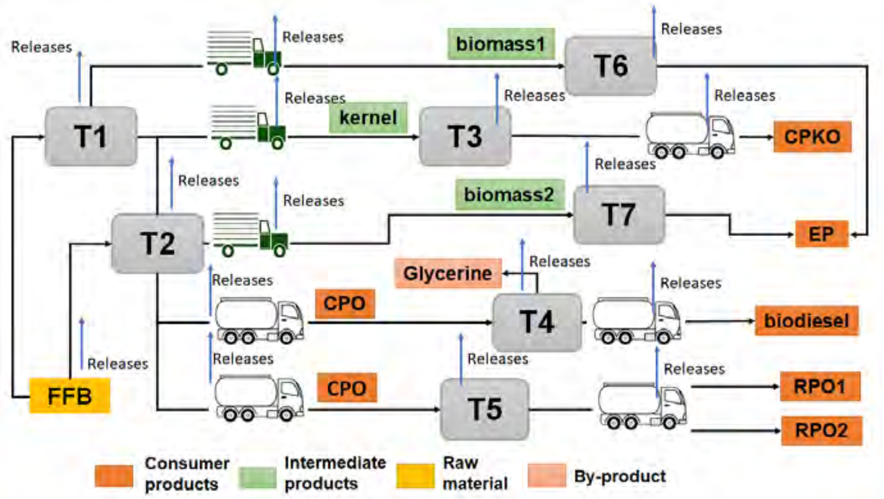


Figure 2: Schematic of the interrelationships between the different palm-based products and processing technologies considered in this study

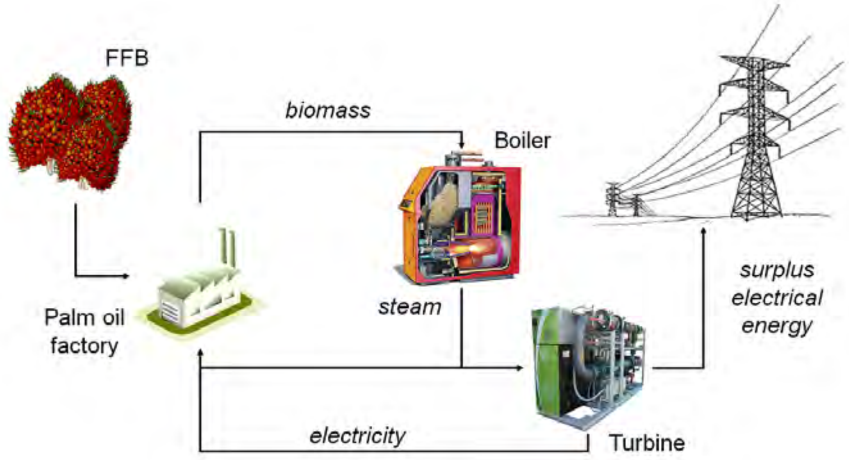


Figure 3: Process of generating electrical energy from biomass

The overall system is divided into nine subsystems: agriculture, seven industrial processes and transportation. The agriculture subsystem involves all activities related to the cultivation and harvest of the palm. The palm fruit (FFB) is made up of empty bunches, exocarp or epicarp, mesocarp or pulp (where CPO is housed), endocarp or shell, and endosperm or kernel. T1 and T2 stand for subsystems (technologies) to produce CPO. In these subsystems, the FFB is crushed (see Figure 2) to extract CPO, leaving the kernel as a by-product. The existence of two different subsystems yielding the same product has to do with different processes that generate two different residual biomass. The CPKO production subsystem comprises the kernel milling to obtain CPKO through T3 technology. The biodiesel production subsystem (T4 technology) involves the acquisition of CPO and the different inputs required to produce biodiesel (transesterification) with glycerin as a by-product. T5 technology is applied in the subsystem for the production of refined oils. This subsystem has two marketable outputs: olein (refined palm oil 1, RPO1) and stearin (refined palm oil 2, RPO2). T1 and T2 technologies generate solid residual biomass of high calorific value, suitable to be burned in boilers to generate electricity by cogeneration. T1 generates biomass 1 and T2, biomass 2. In biomass1, the epicarp, the exhausted pulp, and the endocarp predominate; meanwhile, in biomass2, empty bunches do (Nasution et al. (2014)). Then, T6 technology uses biomass1 and T7 technology, biomass2, to generate electricity. The surplus of electricity (electric power, EP), that is, that which is not consumed by T1 and T2 technologies for its own operation, can be delivered to the Interconnected System (see Figure 3). As for the transportation subsystem, two types of vehicles —medium trucks for kernel, biomass1 and biomass2, and tank trucks for liquid products such as CPO, CPKO, RPO1, RPO2 and biodiesel— are considered.

Therefore, the system considers 12 products in total, which include raw materials, intermediate products, final products and by-products: FFB, CPO, CPKO, RPO1, RPO2, biodiesel, kernel, cake, biomass1, biomass2, glycerin and EP (Figure 2).

Inventory Analysis. In this phase of the LCA, mass and energy balances are performed considering the most relevant inputs and outputs of materials and energy associated with the process. This information will be further converted into environmental impacts in next phase. The inventory data for our problem were obtained from different sources. With regard to the agricultural stage, collected data come from governmental organizations. For the industrial stages, standard mass and energy balance coefficients taken from typical mills and refineries are considered. Data gaps have been covered using specialized literature, handbooks, and databases, as shown in the inventory tables. For transportation, data are retrieved from the Ecoinvent 3 (Frischknecht et al., 2005)

All technologies consume some similar inputs (e.g., water, fuel, etc.), but at different rates. These technologies release in turn different emissions. The reference amount defined for the calculations is 1 t of the main product for T1 and T2 and a given amount of MJ for T6 and T7. The model can decide to leave part of the demand unsatisfied due to limited production capacity or low profitability of the final products. Hence, the production rates vary according to the SC structure chosen by the model after the optimization, which seeks to minimize the environmental impact and maximize the economic profit simultaneously.

Impact Assessment. In this LCA phase, the "gate to gate" process inventories has been translated to environmental impacts by using appropriate impact factors. We select two approaches: on the one hand, a single score from ReCiPe Endpoint (H) V1.12 / World H/H and, on the other hand, 14 categories from ReCiPe Midpoint v1.12 (Huijbregts et al., 2017). This phase computations have been carried out with the support of LCA-software SimaPro® v.9.1.011

Interpretation. Finally, the results of the LCA analysis should be analyzed and a set of conclusions and recommendations formulated. In this regard, the final goal of LCA is to provide good design alternatives for the palm SC. However, LCA lacks a systematic way of generating such alternatives and identifying the best ones. To circumvent these limitations, this work proposes the integration of LCA with an optimization tool, such as former studies have done ((Azapagic and Clift, 1999; Hugo and Pistikopoulos, 2005; Guillén-Gosálbez et al., 2008; Mele et al., 2011)). The resulting multiobjective optimization problem is solved using the ϵ-constraint method to obtain the Pareto front that represent the trade-off between the different objectives considered: environmental versus economic.

4. Mathematical Model

In this section, we present an MILP formulation that embeds the LCA principles described above. It combines the models introduced by Guillén-Gosálbez et al. (2010) and Mele et al. (2011), which address the design of hydrogen and sugarcane SCs, respectively, and by Peña González et al. (2021) for the palm industry.

The model accounts for the option of opening more than one facility in a given region and time period. The environmental concerns are included along with the traditional economic objective, giving rise to a multicriteria decision-making problem that in this work has been addressed as separated bi-criteria problems.

The mathematical formulation considers all possible configurations of the future oil palm SC with its technological features. The following SC activities are included in the analysis:

Production. As a product of the cultivation and harvest tasks in the oil palm fields, the palm fruit (FFB) is transported to plants of T1 or T2 technologies to be crushed and to recover the CPO. The fruit kernel is processed in plants of T3 technology to produce CPKO. In addition, technologies for biodiesel and refined palm oils are included (T4 and T5). Solid biomass generated by T1 and T2 technologies are burnt to produce electricity though technologies T6 and T7, respectively. This electricity is used to power those plants of T1 and T2 technologies and, if there exist a surplus (EP), it can be exported to the grid. Therefore, the model considers seven different technologies, five for palm-derivatives and two for electricity. The model includes a set of 12 products: FFB, CPO, CPKO, RPO1, RPO2, biodiesel, kernel, cake, biomass1, biomass2, glycerin and EP. Each plant of a given technology incurs fixed capital and operating costs and may expand its capacity to meet a specific demand profile.

Storage. The model considers two types of storage, distinguishing between liquid and solid product deposits. For both, it considers the possibility of installation and expansion in each period with the associated capital and operating costs. There are no storage facilities for the FFB, as it must be transported to the factory to be processed within 24 hours after harvest (Sharif et al., 2017).

Transportation. The model proposes two types of vehicles: medium trucks for kernel, biomass1 and biomass2, and tank trucks for liquid products such as CPO, CPKO, RPO1, RPO2 and biodiesel. For any of the means of transportation, the model considers capital and operating costs, with maximum and minimum limits of capacity.

An outline of the equations includes in the model is given next.

4.1. Mass balance

Equation (1) represents the general mass balance, which applies to all products except for electricity. For each material i, the inventory maintained in region r in the previous period ($ST_{i,s,r,t-1}$), plus the amount of produced product ($PT_{i,r,t}$), the amount of purchased raw material ($PU_{i,r,t}$) and the inflow from other regions of the SC ($Q_{i,l,r',r,t}$) must be equal to the stored quantity of i in period t ($ST_{i,s,r,t}$), plus the quantity delivered to customers ($DTS_{i,r,t}$), the sum of the outflows to other regions ($Q_{i,l,r',r,t}$) the amount of i disposed as waste ($W_{i,r,t}$) and the quantity of exported product i ($TAE_{i,r,t}$). The set $IS(i,s)$ links each type of storage with the products i that can be stored in said type, while $IL(i,l)$ links product i with its corresponding transportation mode l.

$$\begin{aligned}\sum_{s\in IS(i,s)} ST_{i,s,r,t-1} \quad &+ \quad PT_{i,r,t} + PU_{i,r,t} + \sum_{l\in IL(i,l)} \sum_{r\neq r'} Q_{i,l,r',r,t} \\ = \sum_{s\in IS(i,s)} ST_{i,s,r,t} \quad &+ \quad DTS_{i,r,t} + \sum_{l\in IL(i,l)} \sum_{r\neq r'} Q_{i,l,r',r,t} + W_{i,r,t} + TAE_{i,r,t} \\ \forall r,t \quad i \neq &\ \text{EP} \end{aligned} \tag{1}$$

Equation (2) indicates that the quantity of products delivered to final consumers must be less than, or equal to, the demand in each region r and time t ($SD_{i,r,t}$). With this, the model is not obliged to satisfy the demand, but to produce as much as possible to maximize profit and minimize the environmental impact without exceeding a maximum investment limit, as will be seen later.

$$DTS_{i,r,t} \leq SD_{i,r,t} \quad \forall i,r,t \quad i \neq \text{EP} \tag{2}$$

4.2. Production

Equation (3) allows us to calculate the total production of material i in each region r and time t ($PT_{i,r,t}$) by adding the production of i that is obtained with each technology p in the same region and period ($PE_{i,p,r,t}$).

$$PT_{i,r,t} = \sum_{p} PE_{i,p,r,t} \;\; \forall i, r, t \tag{3}$$

In equation (4), the by-product and raw materials production rates for each of the technologies are calculated, using balance coefficients $\rho_{p,i}$ and the production rates of the main products. Positive coefficients indicate products, by-products, and residues, and negative coefficients indicate raw materials for each technology. $IM(i,p)$ defines which is the main product i associated with each production technology p.

$$PE_{i,p,r,t} = \rho_{p,i} PE_{i',p,r,t} \;\; \forall i, p, r, t \;\; \forall i' \in IM(i,p) \tag{4}$$

The generation of electricity is modeled as follows. The amount of electrical energy consumed by the production process of CPO (T1 and T2 technologies) is calculated based on the amount of CPO produced and is expressed as $\xi \cdot PE_{\text{CPO},p,r,t}$ with $p =$ T1, T2, where $PE_{\text{CPO},p,r,t}$ represents the amount of CPO produced with T1 and T2 technologies in the region r and time t, and ξ is the conversion factor from CPO to EP (ξ has units of MW(t CPO)$^{-1}$).

The amount of EP that can be sold to the Interconnected System ($ES_{\text{EP},r,t}$) is the surplus between the total amount generated by combustion of biomass1 and biomass2 in a region r and period t ($PT_{\text{EP},r,t}$), minus that consumed by the operation of type T1 and T2 plants ($\xi \cdot PE_{\text{CPO},p,r,t}$), as expressed by equation (5).

$$ES_{\text{EP},r,t} = PT_{\text{EP},r,t} - \xi PE_{\text{CPO},p,r,t} \;\; \forall r, t \; and \; p = \text{T1}, \text{T2} \tag{5}$$

The total amount of electricity generated by the combustion of biomass1 and biomass2 ($PT_{\text{EP},r,t}$) results from the application of equation (3) with $i =$ EP, being $p = \text{T6}, \text{T7}$. The amount of CPO produced in plants with T1 technology ($PE_{i,p,r,t}$) is formed by the sum of two terms, equation (6). $PE1_{i,p,r,t}$ represents the amount of CPO that is produced with T1 and T2 in region r and time t, if there is a surplus of EP in that region and time, and $PE2_{i,p,r,t}$, if there is no such surplus.

$$PE_{i,p,r,t} \;\; = \;\; PE1_{i,p,r,t} + PE2_{i,p,r,t} \;\; \forall r, t \;\; i = \text{CPO}, \; p = \text{T1}, \text{T2} \tag{6}$$

The existence of the two terms in equation (6) is mutually exclusive, which is modeled by associating them to four binary variables $y^1_{r,t}$, $y^2_{r,t}$, $y^3_{r,t}$ and $y^4_{r,t}$, such that $\hat{y}_{r,t} - y^1_{r,t} = 1$ and $\hat{y}_{r,t} - y^3_{r,t} = 1$, if there is a surplus of electricity in r and t after having satisfied the needs of plants with T1 and T2 technologies, and $\hat{y}_{r,t} - y^2_{r,t} = 1$ and $\hat{y}_{r,t} - y^4_{r,t} = 1$, if there is not such a surplus of electricity.

$$\begin{aligned} PE1_{i,p,r,t} &\leq U(\hat{y}_{r,t} - y^1_{r,t}) \quad i = \text{CPO},\ p = \text{T1} \\ PE2_{i,p,r,t} &\leq U(\hat{y}_{r,t} - y^2_{r,t}) \quad i = \text{CPO},\ p = \text{T1} \end{aligned}$$

$$y^2_{r,t} = 1 - y^1_{r,t},\ \forall r,t \tag{7}$$

$$\begin{aligned} PE1_{i,p,r,t} &\leq U(\hat{y}_{r,t} - y^3_{r,t}) \quad i = \text{CPO},\ p = \text{T2} \\ PE2_{i,p,r,t} &\leq U(\hat{y}_{r,t} - y^4_{r,t}) \quad i = \text{CPO},\ p = \text{T2} \end{aligned}$$

$$y^4_{r,t} = 1 - y^3_{r,t},\ \forall r,t \tag{8}$$

with

$$\begin{aligned} \hat{y}_{r,t} \geq&\ \ y^2_{r,t}\ \forall r,t \\ \hat{y}_{r,t} \geq&\ \ y^4_{r,t}\ \forall r,t \\ \tilde{y}_{r,t} =&\ \ 1 - \hat{y}_{r,t}\ \forall r,t \end{aligned} \tag{9}$$

In equations (7) and (8), U is an arbitrarily large scalar. Note that expressions (6),(7) and (8) only apply for i = CPO and p = T1, T2.

The amount of EP delivered to the network in each region r and time t ($DTS_{\text{EP},r,t}$) is equal to the surplus ($ES_{i,r,t}$), if this surplus exists ($\hat{y}_{r,t} - y^1_{r,t} = 1$, $\hat{y}_{r,t} - y^3_{r,t} = 1$), and zero otherwise, that is, when the energy generated by cogeneration plants (T6 and T7) is completely consumed by CPO producing plants ($\hat{y}_{r,t} - y^2_{r,t} = 1$, $\hat{y}_{r,t} - y^4_{r,t} = 1$). This situation is modeled *via* constraints (10). M is an arbitrarily large number corresponding to a *big-M* type formulation (Chinneck, 2008).

$$\begin{aligned} ES_{i,r,t} - M\tilde{y}_{r,t} \leq DTS_{i,r,t} &\leq ES_{i,r,t} + M\tilde{y}_{r,t} \quad i = \text{EP} \\ DTS_{i,r,t} &\leq M(1-\tilde{y}_{r,t}) \end{aligned} \tag{10}$$

The production rate of i with technology p, in region r, is limited between a minimum and a maximum value of capacity, according to equation (11). The lower limit is obtained by multiplying the continuous variable $PCap_{p,r,t}$ (existing capacity) by a value τ between 0 and 1. The upper limit is the capacity itself ($PCap_{p,r,t}$).

$$\tau PCap_{p,r,t} \leq PE_{i,p,r,t} \leq PCap_{p,r,t} \;\; \forall i,p,r,t \tag{11}$$

Equation (12) indicates that the expandability of the technologies in period t ($PCapE_{p,r,t}$)added to the production of the previous period, determines the current production capacity in period t.

$$PCap_{p,r,t} = PCap_{p,r,t-1} + PCapE_{p,r,t} \;\; \forall p,r,t \tag{12}$$

The inequalities (13) represent the expansion capacity of the technologies $PCapE_{p,r,t}$, also between upper and lower limits, which are calculated from the number of plants installed in the region ($NP_{p,r,t}$) and the minimum ($\underline{PCap_p}$) and the maximum ($\overline{PCap_p}$) values of the capacity of each technology p.

$$\underline{PCap_p} NP_{p,r,t} \leq PCapE_{p,r,t} \leq \overline{PCap_p} NP_{p,r,t} \;\; \forall p,r,t \tag{13}$$

particularly,

$$\begin{aligned} NP_{p,r,t} &\leq Uy^2_{r,t} \;\; \forall r,t \;\; and \;\; p = \text{T6} \\ NP_{p,r,t} &\leq Uy^4_{r,t} \;\; \forall r,t \;\; and \;\; p = \text{T7} \end{aligned} \tag{14}$$

The purchase of raw material (FFB) is constrained in equation (15), which is limited by the oil palm production capacity in each region r, in time interval t.

$$PU_{i,r,t} \leq CapCrop_{r,t} \quad i = \text{ FFB}, \;\; \forall r,t \tag{15}$$

4.3. Storage

For any region r, the capacity of a storage technology s, for any time t, is equal to the previous storage capacity plus the expansion capacity ($SCapE_{s,r,t}$) of the current period (equation (16)).

$$SCap_{s,r,t} = SCap_{s,r,t-1} + SCapE_{s,r,t} \;\; \forall s, r, t \tag{16}$$

Equation (17) shows that storage capacity is calculated using the number of warehouse facilities in region r ($NS_{s,r,t}$), and is found between a minimum capacity ($\underline{SCap_s}$) and a maximum capacity ($\overline{SCap_s}$) of storage, for each storage technology.

$$\underline{SCap_s} NS_{s,r,t} \leq SCapE_{s,r,t} \leq \overline{SCap_s} NS_{s,r,t} \;\; \forall s, r, t \tag{17}$$

Inequality (18) shows that storage capacity must be greater than the total inventory ($ST_{i,s,r,t}$) of products stored by the technology s, during the time period t.

$$\sum_{i \in IS(i,s)} ST_{i,s,r,t} \leq SCap_{s,r,t} \;\; \forall s, r, t \tag{18}$$

The average inventory level ($AIL_{i,r,t}$) expected to be maintained throughout the length of the steady-state operation, can be observed in equation (19), and is given by the storage period σ and the amount delivered to clients.

$$AIL_{i,r,t} = \sigma DTS_{i,r,t} \;\; \forall i, r, t \;\; con \;\; i \neq \mathrm{EP} \tag{19}$$

The classic SC management approach (Simchi-Levi et al., 2008) pursues to avoid the problem of fluctuations between supply and demand of products i. This approach consists of setting the storage capacity in region r and time t to a value greater than, or equal to, twice the average inventory for that product, as shown in equation (20).

$$2AIL_{i,r,t} \leq \sum_{s \in IS(i,s)} SCap_{s,r,t} \;\; \forall i, r, t \;\; con \;\; i \neq \mathrm{EP} \tag{20}$$

4.4. Transportation

Inequality (21) limits the flow of materials transported between two regions using the minimum ($\underline{Q_l}$) and maximum ($\overline{Q_l}$) limits of each type of means of transportation l. Equation (22) defines the binary variable $X_{l,r,r',t}$

which takes the value of 1 if there is a transportation route between two regions r and r', and 0 otherwise.

$$\underline{Q_l} X_{l,r,r',t} \leq \sum_{i \in IL(i,l)} Q_{i,l,r,r',t} \leq \overline{Q_l} X_{l,r,r',t} \quad \forall l, t, r, r' \quad (r \neq r') \tag{21}$$

$$X_{l,r,r',t} + X_{l,r',r,t} = 1 \quad \forall l, r, r' \quad (r \neq r') \tag{22}$$

Material i can also be exported by any region with port capacity. Equation (23) indicates that the quantity of exported material cannot exceed port capacity ($\overline{TAE}_{i,r,t}$). This parameter has a non-zero value for regions where international ports are located.

$$TAE_{i,r,t} \leq \overline{TAE}_{i,r,t} \quad \forall i, r, t \tag{23}$$

The quantity of exported materials ($TAE_{i,r,t}$) that appears in the balance mass equation (1), is the sum of all product flows i sent from region r to country b ($AE_{i,b,r,t}$) (equation (24)).

$$TAE_{i,r,t} = \sum_{b} AE_{i,b,r,t} \quad \forall i, r, t \tag{24}$$

4.5. Profitability

This function evaluates the long-term investment and is calculated in the equation (25) as follows

$$Profit = \sum_t Rev_t - \sum_t FOC_t - \sum_t TOC_t - \sum_t EC_t - FCC\mu \tag{25}$$

with $\mu = \frac{ik(1+ik)^t}{(1+ik)^t - 1}$, annualization factor.

Income is obtained from the number of final products sold ($DTS_{i,r,t}$) multiplied by the corresponding prices ($PR_{i,r,t}$) plus the quantity of exported products ($AE_{i,r,b,t}$) multiplied by the international prices according to the country of destination b ($EPR_{i,b}$), (equation (26)). The set of materials i that can be sold domestically and abroad are represented by $SEP(i)$ and $IB(i)$, respectively.

$$Rev_t = \sum_{i \in SEP(i)} \sum_{g} DTS_{i,r,t} PR_{i,r,t} + \sum_{i \in IB(i)} \sum_{r} \sum_{b} AE_{i,r,b,t} EPR_{i,b} \quad \forall t \tag{26}$$

In equation (27), the operating cost of the facilities is obtained by multiplying the unit cost of production ($UPC_{i,p,r,t}$) by the corresponding production rates and the unit cost of storage ($USC_{i,s,r,t}$) times the average inventory level. This cost also includes the cost of waste disposal (DC_t).

$$\begin{aligned} FOC_t &= \sum_i \sum_r \sum_{i \in IM(i,p)} UPC_{i,p,r,t} PE_{i,p,r,t} \\ &+ \sum_i \sum_r \sum_{i \in IS(i,s)} USC_{i,s,r,t} AIL_{i,r,t} + DC_t \quad \forall t \end{aligned} \tag{27}$$

where DC_t is obtained from the generated waste stream ($W_{i,r,t}$) multiplied by the cost of treatment or the tax on discharges ($LT_{i,r}$):

$$DC_t = \sum_i \sum_r W_{i,r,t} LT_{i,r} \quad \forall t \tag{28}$$

Equation (29), is used to evaluate the operating cost of transportation (TOC_t). This variable considers fuel costs (FC_t), labor cost (LC_t), maintenance (MC_t), general expenses (GC_t) and exportation expenses (EC_t). The description of each of these terms is presented in equations (30)-(34).

$$TOC_t = FC_t + LC_t + MC_t + GC_t + EC_t \quad \forall t \tag{29}$$

Fuel costs are calculated according to equation (30):

$$FC_t = \sum_r \sum_{r' \neq r} \sum_l \sum_{i \in IL(i,l)} \left(\frac{2EL_{r,r'}}{FE_l} . \frac{Q_{i,l,r,r',t}}{TCap_l} \right) FP_{l,t} \quad \forall t \tag{30}$$

The factor in parentheses represents the amount of fuel used, where $2EL_{r,r'}$ is the distance traveled in each round trip between regions r and r', FE_l s fuel consumption by transportation mode l, $Q_{i,l,r,r',t}$ represents the flow rate of the material and $TCap_l$ denotes the capacity of transportation mode l. $FP_{l,t}$ is the price of fuel.

Equation (31) shows that the driver's salary ($DW_{l,t}$) multiplied by the total delivery time (term shown in brackets) allow calculating the cost of transportation labor. The parameters LUT_l and SP_l denote the upload/download time and the average speed of transportation mode l, respectively.

$$LC_t = \sum_{r} \sum_{r' \neq r} \sum_{l} DW_{l,t} \sum_{i \in IL(i,l)} \left[\frac{Q_{i,l,r,r',t}}{TCap_l} \left(\frac{2EL_{r,r'}}{SP_l} + LUT_l \right) \right] \quad \forall t \tag{31}$$

Maintenance cost represents the general maintenance of the transportation units and is a function of the cost per unit of distance traveled (ME_l). The total route is given by equation (32).

$$MC_t = \sum_{r} \sum_{r' \neq r} \sum_{l} \sum_{i \in IL(i,l)} ME_l \frac{2EL_{r,r'} Q_{i,l,r,r',t}}{TCap_l} \quad \forall t \tag{32}$$

General expenses (equation (33)) are obtained by multiplying the general unitary expenses ($GE_{l,t}$) by the number of transportation units ($NT_{l,t}$). The former includes transportation insurance, license and registration fees, and outstanding debts.

$$GC_t = \sum_{l} \sum_{t' \leq t} GE_{l,t} NT_{l,t'} \quad \forall t \tag{33}$$

Exportation expenses (EC_t) are calculated in equation (34), taking into account the quantity of products sent from the region r to country b and the unit freight cost ($FRC_{i,b}$).

$$EC_t = \sum_{i \in IB(i)} \sum_{r} \sum_{b} AE_{i,r,b,t} FRC_{i,b} \quad \forall t \tag{34}$$

FCC (equation (35)) represents the total investment of capital, determined by capacity expansions carried out in plants and warehouses, as well as purchases of transportation units over the time horizon.

$$\begin{aligned}
FCC &= \sum_p \sum_r \sum_t \left(\alpha^{PL}_{p,r,t} \cdot NP_{p,r,t} + \beta^{PL}_{p,r,t} \cdot PCapE_{p,r,t}\right) \\
&+ \xi \cdot \sum_p \sum_r PE2_{\mathrm{CPO,T1},r,t} \cdot PR_{\mathrm{EP},r,t} \\
&+ \xi \cdot \sum_p \sum_r PE2_{\mathrm{CPO,T2},r,t} \cdot PR_{\mathrm{EP},r,t} \\
&+ \sum_s \sum_r \sum_t \left(\alpha^{S}_{s,r,t} \cdot NS_{s,r,t} + \beta^{S}_{s,r,t} \cdot SCapE_{s,r,t}\right) \\
&+ \sum_l \sum_t NT_{l,t} \cdot TMC_{l,t} \qquad (35)
\end{aligned}$$

The parameters $\alpha^{PL}_{p,r,t}, \beta^{PL}_{p,r,t}$ are the fixed and the variable capital costs of plants, respectively. In the same way, $\alpha^{S}_{s,r,t}, \beta^{S}_{s,r,t}$ are the fixed and the variable capital costs, respectively, of warehouses. $PR_{\mathrm{EP},r,t}$ is the price of electricity, which multiplies $\xi \cdot PE2_{\mathrm{CPO,T1},r,t}$ and $\xi \cdot PE2_{\mathrm{CPO,T2},r,t}$ if the energy generated by the combustion of biomass has not been enough to satisfy the consumption of plants with technologies T1 and T2. $TMC_{l,t}$ is the investment cost related to the acquisition of transportation units of mode l. The average number of trucks required to attend the flow between different regions ($NT_{l,t}$) is calculated by the flow of products between regions, the availability of transportation mode (avl_l), the capacity of the shipping containers, the average distance traveled between regions, and the average speed and the time of loading/unloading, as presented in inequality (36):

$$\sum_{i \in IL(i,l)} \sum_r \sum_{r' \neq r} \sum_t \frac{Q_{i,l,r,r',t}}{avl_l TCap_l} \left(\frac{2EL_{r,r'}}{SP_l} + LUT_l\right) \leq \sum_{t \leq T} NT_{l,t} \quad \forall l \qquad (36)$$

The total amount of the capital investment is restricted to an upper limit, as indicated by inequality (37):

$$FCC \leq \overline{FCC} \qquad (37)$$

The cost of capital is uniformly distributed over time, according to the equation (38) to determine the amortization term ($FTDC_t$)

$$FTDC_t = \frac{FCC}{T} \quad \forall t \qquad (38)$$

4.6. Environmental Impact

The main sources of environmental issues associated with the SC operation are the production of the main feedstock, FFB, the manufacturing tasks, and the transportation of materials between regions. Mathematically, the inventory of emissions due to the operation of the network can be expressed as a function of some continuous variables of the model. Specifically, the entries of the life cycle inventory for each chemical m (LCI_m) can be calculated from the production rates at the plants ($PE_{i,p,r,t}$), and the transportation flows ($Q_{i,l,r,r\prime,t}$), as stated in equation (39).

$$\begin{aligned} LCI_m \quad = \quad & \sum_{i \in IM(i,p)} \sum_{p \in IM(i,p)} \sum_{r} \sum_{t} PE_{i,p,r,t} \cdot \omega_m^{Pr_a} \\ + \quad & \sum_{i \in IM(i,p)} \sum_{p \in IM(i,p)} \sum_{r} \sum_{t} \left(PE2_{i,p,r,t} \cdot \omega_m^{Pr_e} + PE1_{i,p,r,t} \cdot \omega_m^{Pr_e^\star} \right) \\ + \quad & \sum_{i \in IM(i,p)} \sum_{p \in IM(i,p)} \sum_{r} \sum_{t} \left(PE2_{i,p,r,t} \cdot \omega_m^{Pr_e} + PE1_{i,p,r,t} \cdot \omega_m^{Pr_e^\star} \right) \\ + \quad & \sum_{i \in IM(i,p)} \sum_{p \in IM(i,p)} \sum_{p} \sum_{r} \sum_{t} PE_{i,p,r,t} \cdot \omega_{p,m}^{Pr} \\ + \quad & \sum_{i} \sum_{p} \sum_{r' \neq r} \sum_{l \in IL(i,l)} \sum_{t} Q_{i,r,r',t} \cdot EL_{r,r'} \cdot \omega_{l,m}^{Tr} \end{aligned} \qquad (39)$$

The first term in equation (39) represents the impacts associated with the agricultural stage. The second and third terms in equation (39) consider the impacts by the production process of CPO. The fourth term represents the impacts associated with the manufacturing tasks, which include CPKO manufacturing, RPO1 and RPO2 manufacturing, biodiesel manufacturing and the electricity generation by combustion of biomass1 or biomass2. Finally the fifth term in equation (39) considers the emissions due to the transportation tasks. $\omega_m^{Pr_a}$, $\omega_m^{Pr_e}$, $\omega_m^{Pr_e^\star}$, $\omega_{p,m}^{Pr}$ and $\omega_{l,m}^{Tr}$ denote the "gate to gate" life cycle inventory entries (i.e., emissions released to the environment or resource taken from the ecosphere) associated with chemical m expressed per reference flow of each activity. In the manufacturing tasks, the reference flow is one unit of main product produced. For the transportation tasks, the reference flow is one unit of mass transported one unit of distance.

The environmental impact caused is calculated by multiplying the life cycle inventory entries with the corresponding characterization factors associated to chemical specie m (d_m), as stated in equation (40)

$$EI = \sum_m d_m \cdot LCI_m \tag{40}$$

The variable EI is the environmental metric to be minimized, such as those derived from the ReCiPe method described in the section before.

4.7. Multiobjective Problem

The bi-objective MILP formulation can be expressed in compact form as follows:

$$\min_{x,X,N} \{-Profit(x,X,N); EI(x,X,N)\} \tag{41}$$

$$\text{subjected to constraints (1)-(40)}$$

$$x \subset \mathbb{R}, X \subset \{0,1\}, N \subset \mathbb{Z}^+$$

where x represents the continuous variables of the problem (capacity expansions, production rates, inventory levels, and input flows), X represents the binary variables (that is, the existence of transportation links and logical variables related to the flow of EP), and N represents the positive integer variables which, in this case, are the number of plants, storage facilities, and transportation units of each kind. The solution to this problem is given by a set of Pareto alternatives representing the optimal trade-off between the objectives considered in the analysis.

In this work, the Pareto solutions are determined *via* $\epsilon-$constraint method (Ehrgott, 2005), which entails solving a set of instances of the following single-objective problem MOP1 (42) for different values of the auxiliary parameter ϵ:

$$\min_{x,X,N} \{-Profit(x,X,N)\} \quad \text{(MOP1)} \tag{42}$$

$$\text{subjected to constraints (1)-(40)}$$

$$EI(x, X, N) \leq \epsilon$$

$$\underline{\epsilon} \leq \epsilon \leq \overline{\epsilon}$$

$$x \subset \mathbb{R}, X \subset \{0, 1\}, N \subset \mathbb{Z}^{+}$$

where the lower and upper limits of ϵ (i.e., $\epsilon \in [\underline{\epsilon}; \overline{\epsilon}]$) are obtained from the optimization of each separate scalar objective:

$$(\overline{x}\overline{XN}) = \arg\min_{x,X,N}\{EI(x, X, N)\} \quad (\text{MOP1}a) \tag{43}$$

subjected to constraints (1)-(40)

$$x \subset \mathbb{R}, X \subset \{0, 1\}, N \subset \mathbb{Z}^{+}$$

which defines $\underline{\epsilon} = EI(\overline{x}\overline{XN})$ and

$$(\widehat{x}\widehat{X}\widehat{N}) \arg\min_{x,X,N} = \{-Profit(x, X, N)\} \quad (\text{MOP1}b) \tag{44}$$

subjected to constraints (1)-(40)

$$x \subset \mathbb{R}, X \subset \{0, 1\}, N \subset \mathbb{Z}^{+}$$

which defines $\overline{\epsilon} = EI(\widehat{x}\widehat{X}\widehat{N})$.

5. Case Study

To apply the model, 31 of the 32 departments in which Colombia is administratively divided were considered. The archipelago of San Andrés, Providencia y Santa Catalina was excluded due to its lack of relevance to oil palm industry. The multi-period model was applied for a time horizon of five years. Each of these regions has an internal maximum demand associated with the four main products (RPO1, RPO2, biodiesel, and EP). EP is considered to be sold only in the internal market, while, CPO, CPKO, RPO1, RPO2, and biodiesel are exportable, without allocation of external demand. An annual increase in demand is chosen as the demand pattern in two of the products: an increase of 15% for biodiesel and 10% for EP. The demand for RPO1 and RPO2 remains constant. However, the model is flexible enough to represent different demand patterns as chosen by the analyst.

Tables A1 - A6 in the Appendix display the main "gate to gate" data of inputs and outputs associated with the subsystems. The boundaries of the analysis have been expanded in order to account for the impact associated with the production of every auxiliary material or energy input to the system (e.g., fertilizers, chemicals, etc.). In line with a common LCA practice, we have neglected the environmental impact associated with the production of capital equipment.

Table 1 shows the national demand for final products and the production capacity of FFB (t/year) in each region (Fedepalma, 2019), while Table 2 shows the distances between regions (Google maps, 2020). In the case of the demand for EP, the information was taken from the Ministry of Mines and Energy of Colombia (UPME-MEN, 2019). Table 3 and Table 4 presents the maximum and minimum limits of the production capacity of the main products in each technology, and the coefficients of balance of input for the different technologies (Nasution et al., 2014; Reeb et al., 2014). Table 5 presents the parameters used to calculate capital and operating costs for the different transportation modes. The upper limit of the investment capital is set at USD 25 billion.

Table 6 shows the parameters that are used to evaluate the capital costs of the different production technologies, while Table 7 indicates those used to evaluate the capital costs for different storage technologies. The unit costs of production for CPO, CPKO, RPO1, RPO2, biodiesel, and EP are 75, 25, 18, 18, 66, and 17 USD/t, respectively. The unit storage cost is 1.5 USD/(t year) for all types of materials. The tax rate (φ), the residual value (sv) and the interest rate (ik) are 0.1, 0.2 and 0.19, respectively. Finally, the landfill tax is equal to 0.05 USD/t according to Law 99 of 1993 (CNRC, 1993).

The bi-criteria model is written in GAMS and solved with CPLEX on a PC, with an Intel® Core™ i5-4200U processor, 8 GB RAM and CPU@1.60GHz. Particularly, we generated one Pareto set: profit versus environmental single. Each instance of problem MOP1 was solved to global optimality. The resulting optimization model contains 177,529 equations, 113,048 simple variables, and 11,635 discrete variables. The MILP was solved to an optimality gap of less than 1%, and a CPU time of about 747 hours.

Table 1: Domestic demand of final products and FFB production capacity (t/year)

Region (state)		Final product demand				FFB production capacity
	Identifier	RPO1	RPO2	biodiesel	EP	
Amazonas	R01	24020	24020	3328	0	0
Antioquia	R02	27628,7	24869,1	237120,6	30486780000	1061386,3
Arauca	R03	24020	24020	158080,4	6421680000	0
Atlántico	R04	24020	24020	169728,4	9724628571	0
Bolívar	R05	40386,9	27871	169728,4	9724628571	4813787,5
Boyacá	R06	24020	24020	237120,6	6421680000	0
Caldas	R07	24020	24020	79040,2	3315600000	0
Caquetá	R08	24029,6	24022,3	79040,2	3915600000	2835,4
Casanare	R09	62656	33110,8	237120,6	6421680000	11363520,7
Cauca	R10	24020	24020	178048,5	2474400000	0
Cesar	R11	90609,1	39688	169728,4	9724628571	19585017,2
Choco	R12	24020	24020	237120,6	5380020000	0
Córdoba	R13	24020	24020	169728,4	9724628571	0
Cundinamarca	R14	24398,4	24109	237120,6	48645792000	111293,4
Guainía	R15	24020	24020	3328	0	0
Guaviare	R16	24020	24020	3328	6080724000	0
Huila	R17	24020	24020	79040,2	3915600000	0
La Guajira	R18	24020	24020	169728,4	9724628571	0
Magdalena	R19	68149	34403,3	169728,4	9724628571	12979101,4
Meta	R20	127917,1	48466,4	237120,6	6080724000	30557977,5
Nariño	R21	35295,5	26673	178048,5	2474400000	3316319,4
Norte de Santander	R22	49173,1	29938,4	158080,4	6421680000	7397980,2
Putumayo	R23	24020	24020	178048,5	2474400000	0
Quindío	R24	24020	24020	79040,2	3315600000	0
Risaralda	R25	24020	24020	79040,2	3315600000	0
Santander	R26	69411,6	34700,4	158080,4	6421680000	13350484
Sucre	R27	24020	24020	169728,4	9724628571	0
Tolima	R28	24020	24020	79040,2	3915600000	0
Valle del Cauca	R29	24020	24020	178048,5	26658000000	0
Vaupés	R30	24020	24020	3328	0	0
Vichada	R31	26002,2	24486,4	3328	0	583016,2

Table 3: Material balance coefficients and maximum and minimum bounds for the production technologies T1 to T5

	Feedstock, products and waste											Production bounds (t of main product per year)	
	FFB	CPO	CPKO	RPO1	RPO2	biodiesel	kernel	cake	biomass1	biomass2	glycerine	Min.	Max.
T1	-4,683	1	0	0	0	0	0,181	0	0,836	0	0	93600	187200
T2	-4,683	1	0	0	0	0	0,181	0	0	1,886	0	93600	187200
T3	0	0	1	0	0	0	-2,083	1,120	0	0	0	93600	187200
T4	0	-1,09	0	0	0	1	0	0	0	0	0,22	20000	200000
T5	0	-1,319	0	1	0,25	0	0	0	0	0	0	93600	187200

Table 4: Balance coefficients and maximum and minimum bounds for the electrical production technologies

	Feedstock and products			Production bounds (MJ of main product per year)	
	biomass1	biomass2	EP	Min.	Max.
T6	-0,002	0	1	311040000	311040000
T7	0	-0,0002	1	648000000	648000000

Table 5: Parameters used to calculate the capital and operating costs for different transportation modes. Peña González et al. (2021)

	Medium truck	Tanker truck
Average speed (km/h)	60	60
Capacity (t/trip)	25	20
Availability of transportation mode (h/day)	16	16
Cost of transportation mode (USD)	350000	315000
Driver wage(USD/h)	4,4	4,4
Fuel consumption (km/L)	2,5	360
Fuel price (USD/L)	0,8	0,8
General expenses (USD/day)	16,3	12,260
Product load/unload time (h/trip)	6	6
Maintenance expenses (USD/km)	0,0976	0,0976

Table 2: Matrix of distances between regions (km)

	R01	R02	R03	R04	R05	R06	R07	R08	R09	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20	R21	R22	R23	R24	R25	R26	R27	R28	R29	R30	R31
R01	0	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
R02		0	988	716	670	421	206	813	626	565	747	232	442	417	N.A.	809	580	892	838	532	815	584	897	303	264	391	472	416	436	N.A.	1379
R03			0	957	1071	579	1000	1274	363	1307	948	1292	1089	718	N.A.	899	1039	846	1017	614	1558	392	1358	1006	1045	438	1040	926	1186	N.A.	1329
R04				0	114	862	999	1399	1066	1383	301	944	370	1002	N.A.	1394	1163	268	107	1117	1634	676	1482	1088	1047	647	254	1002	1254	N.A.	1964
R05					0	958	861	1495	1163	1212	398	895	281	1099	N.A.	1491	1260	382	221	1214	1463	773	1579	921	877	682	199	1099	1083	N.A.	2032
R06						0	422	696	216	730	726	715	755	141	N.A.	539	461	871	817	262	980	417	780	428	467	282	878	348	609	N.A.	1109
R07							0	661	637	388	863	303	636	293	N.A.	687	381	1008	955	410	638	700	655	97	52	507	666	176	259	N.A.	1257
R08								0	904	267	1263	812	1224	549	N.A.	915	236	1408	1354	638	390	1100	245	526	565	907	1415	446	377	N.A.	1485
R09									0	945	924	930	953	356	N.A.	536	677	1069	1016	252	1196	493	995	644	683	481	1077	564	824	N.A.	967
R10										0	1251	555	991	586	N.A.	953	274	1396	1343	676	246	1086	268	310	340	894	1020	395	141	N.A.	1523
R11											0	974	433	866	N.A.	1258	1027	159	256	981	1497	540	1346	951	911	449	317	866	1118	N.A.	1828
R12												0	670	566	N.A.	933	576	1119	1066	656	805	811	819	292	253	618	700	371	425	N.A.	1503
R13													0	790	N.A.	1183	951	605	444	905	1200	811	1270	659	614	721	122	790	821	N.A.	1752
R14														0	N.A.	400	314	1010	956	123	833	556	633	281	320	426	856	201	462	N.A.	970
R15															0	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.	N.A.
R16																0	690	1411	1357	284	1209	962	1008	657	696	832	1418	577	837	N.A.	1131
R17																	0	1172	1119	402	520	864	320	290	329	671	1180	210	323	N.A.	1249
R18																		0	172	1127	1646	686	1492	1097	1056	595	488	1011	1266	N.A.	1974
R19																			0	1073	1588	632	1438	1043	1003	541	325	958	1208	N.A.	1920
R20																				0	924	578	724	373	412	520	973	293	553	N.A.	852
R21																					0	1332	146	556	585	1140	1266	641	387	N.A.	1768
R22																						0	1181	786	746	195	693	701	953	N.A.	1523
R23																							0	573	602	991	1499	530	404	N.A.	1569
R24																								0	49	601	727	86	179	N.A.	1217
R25																									0	557	682	124	209	N.A.	1256
R26																										0	602	511	763	N.A.	1473
R27																											0	857	887	N.A.	1819
R28																												0	265	N.A.	1137
R29																													0	N.A.	1397
R30																														0	N.A.
R31																															0

Table 6: Parameters used to evaluate the capital cost for different production technologies. Source: personal communications with experts

Technologies	$\alpha^{PL}_{p,r,t}$ (USD)	$\beta^{PL}_{p,r,t}$ (USD$\cdot$ y/t)
T1	40.000.000	145
T2	40.000.000	145
T3	4.000.000	87
T4	22.000.000	115
T5	2.500.000	43
T6	3.600.000	135
T7	9.500.000	135

Table 7: Parameters used to evaluate the capital cost for different storage technologies. Source: personal communications with experts

Technologies	$\alpha^{S}_{s,r,t}$ (USD)	$\beta^{S}_{s,r,t}$ (USD$\cdot$ y/t)
S1	160.000	151
S2	1.500.000	180

6. Results and Discussion

We outline the Pareto optimal front through the computation of ten Pareto optimal points being one of them the trivial solution of not installing plants. We refer to the remaining nine points with $p1, \ldots, p9$. The Pareto points are obtained taken different values of the parameter ϵ evenly spaced between minimum and maximum values (Equations 42 - 44). The Pareto front represents the trade-off between economic profitability, in USD, and the environmental impact single score, in “eco-points”(Pt). Figure 4 shows the obtained results. As observed, reductions in the single score can only be achieved at the expense of compromising the profit. The profitability decreases from USD 2.87×10^{11} to 2.3×10^{10} between the two extreme solutions (p1 and p9), i.e., minimum environmental impact and maximum profit. Such an economic loss entails a descent of the environmental score from 3.2×10^{9} to 3.6×10^{8} Pt, and, in the CO_2 eq. emissions, from 3,98$\times 10^{9}$ kg CO_2 to 3,71 $\times 10^{8}$ kg CO_2 eq.. Note that each point of the Pareto set represents a different SC configuration operating under a set of specific conditions. Figure 5 depicts the number of plants of each technology that the optimization

590 model decides to install in each Pareto point.

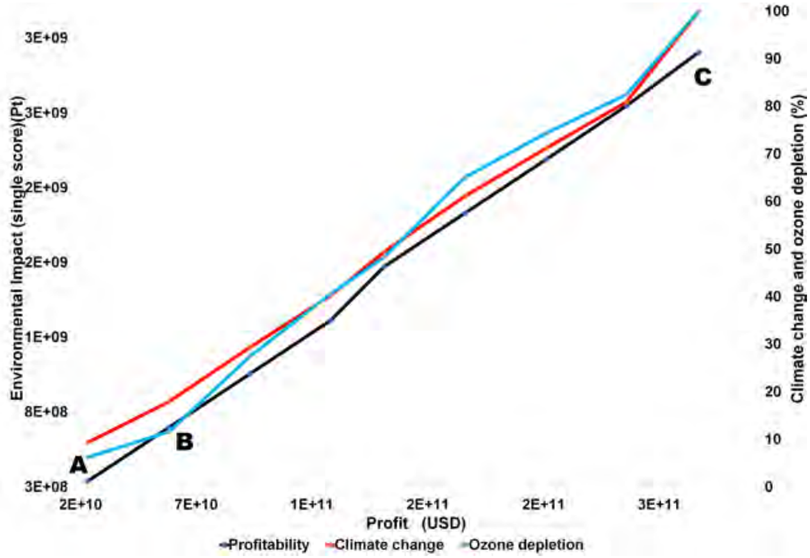


Figure 4: Pareto curve of environmental impact (single score) vs profit, and corresponding values of climate change and ozone depletion as percentages of the impact in solution p9

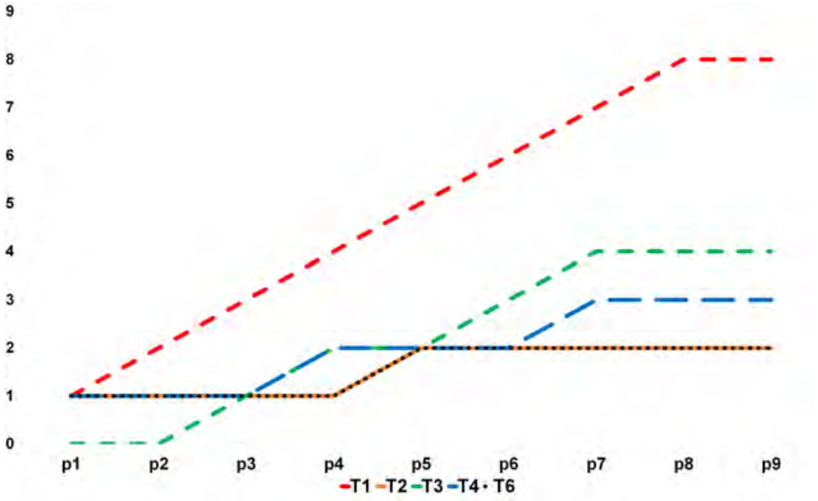
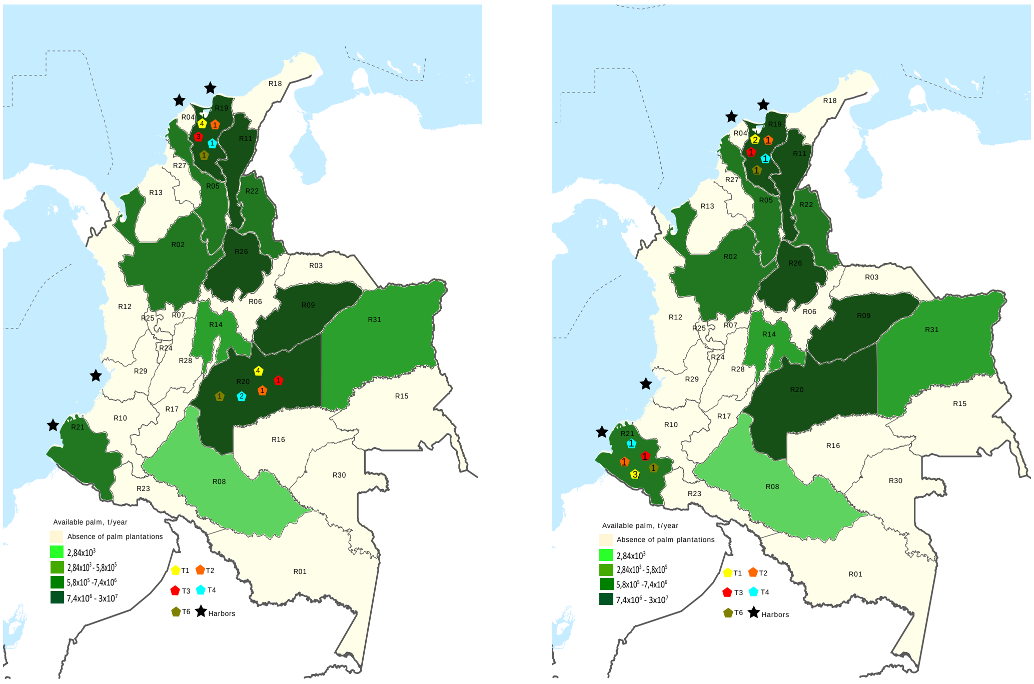


Figure 5: Number of technologies installed for nine of the Pareto points

Two clearly differentiated areas can be distinguished in the Pareto front, which entail different strategic and planning decisions (Figure 4). The short interval AB comprises SC structures that produce CPO, RPO and EP via technologies T1, T2, T4, and T6. The solutions within this region mostly differ each other in the planning decisions. The main difference between solutions lying in the interval AB and those in BC is the absence of technology T3. Solutions in the interval BC show a growing number of biodiesel production plants in regions R19 and R20.



6.1: Pareto point p9 6.2: Pareto point p4

Figure 6: (6.1) SC optimal configuration of Pareto point p9 (maximum profit). (6.2) SC optimal configuration of Pareto point p4

From now on, the analysis will focus on the extreme solution of the Pareto set (p9) that corresponds to the SC design of greatest profit and at the same time greatest environmental impact among the points analyzed. In this solution, the SC includes eight plants of technology T1, two of technology T2 that convert FFB into CPO, four of technology T3, three of technology T4 and two of technology T6 that convert biomass into EP. All these production facilities are located in two palm-producing regions as shown in Figure 6.1: R19 (Magdalena) and R20 (Meta).

Two technologies stood out for the number of installations in the solution of maximum profit: T1 and T3. If these two technologies are considered together, installed plants represent 63% of the total installed (Figure 5 and 6.1). The number of plants that generate electricity from biomass T6, represent 11%. The amount of plants using T4 technology to produce RPO, correspond to 25%. Since we start from an initial solution in which there are no plants or warehouses installed, the optimal solution suggests the installation of all the plants in the first year of the analyzed period.

Then the solution p9 is compared with the current configuration published by different Colombian organizations: SISPA by Fedepalma (2019), the Colombian Ministry of Energy UPME-MEN (2019), the National Federation of Biofuels of Colombia Fedebicombustibles (2020) and the National Agency for Infrastructure ANI (2020). The model proposes to install fewer plants of T1 technology (8) and T2 technology (2). For the production plants of biodiesel (T3), less than the 52 registered in the last census, carried out in 2011 (Fedepalma, 2019). For the production of biodiesel (T3), data taken from (Fedebicombustibles, 2020) show a current configuration of 12 biodiesel production plants in Colombia. In this case, the model raises the possibility of installing four plants.

The electricity generation in solution p9 constitutes a demand satisfaction of only 3.2% in R19 and 5.1% in R20, which however represents an enrichment of renewable energy for the national matrix. In addition, the biodiesel demand is satisfied to some extent in four regions: R04 (Atlántico), R19 (La Guajira), R19 and R20, with 100% demand satisfaction in R04 and R19 (Table 8).

Table 8: Demand satisfaction for biodiesel RPO and EP, in optimal Pareto points p9 and p4

		Pareto point: p9	Pareto point: p4	Pareto point: p9	Pareto point: p4
Region (state)	Associated region	Biodiesel		EP	
		Satisfaction (%)	Satisfaction (%)	Satisfaction (%)	Satisfaction (%)
Atlántico	R04	100	0	0	0
La Guajira	R18	28	0	0	0
Magdalena	R19	100	0	3.2	0
Meta	R20	49	58.5	5.1	7

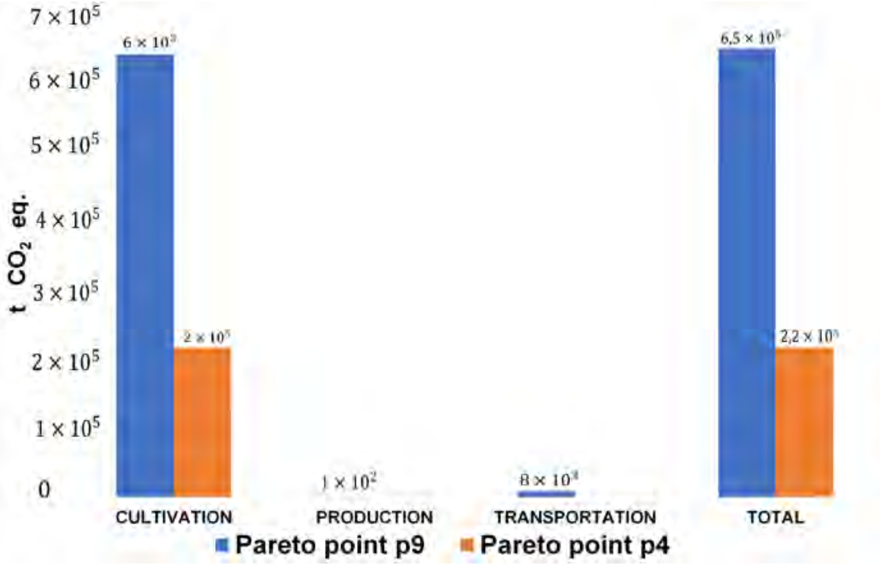


Figure 7: Contribution of different SC echelons to the climate change for the extreme solutions p9 and p4 considering the whole planning horizon

Figure 7 shows the contribution of each SC echelon (i.e., cultivation, production, and transportation) to the environmental impact in Pareto points p9 and p4 (Azapagic and Clift, 1999; Castanheira and Freire, 2017), in terms of climate change. The cultivation of FFB shows the largest contribution to the impact which is in agreement with the works of other authors who say that the agricultural stage is critical in the environmental impact associated with the palm value chain (Munasinghe et al., 2019; Wahyono et al., 2019). It is interesting to notice that the impact due to transportation tasks is rather small in comparison with that associated with the cultivation tasks. In the entire time horizon (5 years), climate change shows important differences if comparing two Pareto points (p9 and p4). For p4, is 2.2×10^8 kg CO_2 eq., and for p9, is 6.5×10^8 kg CO_2 eq.

As can be seen, the model is flexible enough to contemplate other situations such as the consideration of a previously established palm SC. This can be used as a starting point to retrofit leading to an optimal configuration. Other demand patterns and longer time horizons can also be considered.

7. Conclusions

The present work studies the optimal design and planning of the oil palm SC, including the possibility of producing energy from the biomass waste generated. The optimization problem is modelled as a multi-period multi-objective MILP. The formulation seeks to maximize the overall profit and minimize the environmental impact, which leads to Pareto solutions that represent the existing trade-offs between the chosen objective functions.

The benefits of using this model are successfully demonstrated through a case study of the palm industry in Colombia. Specific data from the national palm SC is used as much as possible. The proposed model serves as a quantitative tool for decision-making in the area of strategic design and optimum planning of the industrialization of biomass SC in general, and the Colombian oil palm SC in particular. The obtained solutions indicate a more rational distribution of the productive units, taken into account economic and environmental considerations, in an international context in which the palm industry is highly questioned due to its socio-environmental implications.

The Pareto solutions provide valuable insight into the design problem and suggest alternatives leading to economic and environmental improvements, since shows how some environmental savings can be attained by properly adjusting the SC profit. The environmental impact is considered through the inclusion of the LCA-based metrics into the optimization framework, which ensures a holistic vision of the environmental problem and is the state-of-the-art methodology in this regard.

The application of this type of tools would allow stakeholders for strategic planning that encourages the installation of industrial plants in locations more accessible to markets, in addition to improving the regional development, increasing employment and social welfare. For future research, it is considered important to complement the considerations of parametric uncertainty study for this SC.

Acknowledgements

The authors are grateful for the support of the Government of Magdalena, the project of scholarships General System of Regalías (SGR) doctorate Nacional Colombia [Not. 672], the Universidad del Norte (Colombia) and the CYKLOS research group of the National University of Tucumán (Argentina).

Notation

Indices
b = country for exportation
i = materials
l = transportation modes
m = Single score
p = manufacturing technologies
r = region zones
s = storage technologies
t = time periods
Sets
$IB(i)$ = set of materials that can be exported
$IL(i, l)$ = set of transportation model corresponding to product i
$IM(i, p)$ = set of ordered pairs that link main products i to technologies p
$SEP(i)$ = set of products that can be sold
$IS(i, s)$ = set of ordered pairs that link materials i to storage technologies s
Parameters
$\alpha^{PL}_{p,r,t}$ = fixed investment coefficient for technology p
$\alpha^{S}_{s,r,t}$ = fixed investment coefficient for storage technology s
$\beta^{PL}_{p,r,t}$ = variable investment coefficient for technology p
$\beta^{S}_{s,r,t}$ = variable investment coefficient for storage technology s
ξ = electricity conversion factor
$\rho_{p,i}$ =Balance coefficient associated with material/energy i and technology p
σ = storage period
τ = minimum desired percentage of the available installed capacity
φ = tax rate
avl_l = availability of transportation mode l
$CapCrop_{r,t}$ = total capacity of FFB plantations in region r in time t
d_m = damage factor associated to chemical specie m
$DW_{l,t}$ = driver wage
$EL_{r,r'}$ = distance between r and r'
$EPR_{i,b}$ = price of material i in country b
$\overline{FCI}$ = upper limit on the capital investment
FE_l = fuel consumption of transportation mode l
$FP_{l,t}$ = fuel price
$FRC_{i,b}$ = freight cost of material i
$GE_{l,t}$ = general expenses of transportation mode l

ik = interest rate

$LT_{i,r}$ = amount of waste and landfill tax

LUT_l = loading/unloading time of transportation mode l

M = big enough scalar

ME_l = maintenance expenses of transportation mode l

$\overline{PCap_p}$ = maximum capacity of production technology p

$\underline{PCap_p}$ = minimum capacity of production technology p

$PR_{i,r,t}$ = prices of final products i

$\overline{Q_l}$ = maximum capacity of transportation mode l

$\underline{Q_l}$ = minimum capacity of transportation mode l

$\overline{Scap_s}$ = maximum capacity of storage technology s

$\underline{Scap_s}$ = minimum capacity of storage technology s

$SD_{i,r,t}$ = actual demand of product i in region r in time t

SP_l = average speed of transportation mode l

sv = salvage value

T = number of time intervals

$TCap_l$ = capacity of transportation mode l

$\overline{TAE}_{i,r,t}$ = exportation capacity of harbors for product i in region r in time t

$TMC_{l,t}$ = cost of establishing transportation mode l in period t

U = big enough scalar

$UPC_{i,p,r,t}$ = unit production cost

$USC_{i,p,r,t}$ = unit storage cost

Variables

$AIL_{i,r,t}$ = average inventory level of product i in region r in period t

$AE_{i,b,r,t}$ = amount of exported material i from region r to country b in time t

CF_t = cash flow in time period t

DC_t = disposal cost in time period t

$DTS_{i,r,t}$ = delivered amount of material i in region r in period t

EI_m = environmental impact

EC_t = exportation cost in time t

$ES_{i,r,t}$ = delivered amount of MJ to region r

FCC = fixed capital investment

FOC_t = facility operating cost in time period t

$FTDC_t$ = fraction of the total depreciable capital in time period t

GC_t = general cost in time period t

LC_t = labor cost in time period t

LCI_m = life cycle inventory entry of chemical m

MC_t = maintenance cost in time period t

NE_t = net earnings in time period t

$NP_{p,r,t}$ = number of plants with technology p established in region r and time period t

$NS_{s,r,t}$ = number of storages with storage technology s established in region r and time period t

$NT_{l,t}$ = number of transportation units l acquired in time period t

$PCap_{p,r,t}$ = existing capacity of technology p in region r and time period t

$PCapE_{p,r,t}$ = capacity expansion of technology p in region r and time period t

$PE_{i,p,r,t}$ = production rate of material i associated with technology p in region r and time period t

$PE1_{i,r,t}$ =quantity of CPO produced by technology T1 and T2 if there is a positive surplus of electrical energy in a region r at time t

$PE2_{i,r,t}$ = quantity of CPO produced by technology T1 and T2 if there is not any surplus of electrical energy in a region r at time t

$PT_{i,r,t}$ = total production rate of material i in region r and time period t

$PU_{i,r,t}$ = purchase of material i in region r in time t

$Q_{i,l,r,r',t}$ = flow rate of material i transported by mode l from region r to region r' in time period t

Rev_t = revenues in time t

$SCap_{s,r,t}$ = capacity of storage s in region r in time period t

$SCapE_{s,r,t}$ = expansion of capacity of storage s in region r in time t

$ST_{i,s,r,t}$ = total inventory of material i in region r stored by technology s in time period t

$TAE_{i,r,t}$ = total amount of exported material i from region r in time t

TOC_t = transportation operating cost in time period t

$X_{l,r,r',t}$ = binary variable, which is equal to 1 if material flow between two regions r and r' is established and 0 otherwise

$Y^1_{r,t}$ = binary variable, is equal to 1, if there is a surplus of electricity in r and t after satisfying the needs plants with T1 technology

$Y^2_{r,t}$ = binary variable, is equal to 1, if there is no a surplus of electricity in r and t after satisfying the needs plants with T1 technology

$Y^3_{r,t}$ = binary variable, is equal to 1, if there is a surplus of electricity in r and t after satisfying the needs plants with T2 technology

$Y^4_{r,t}$ = binary variable, is equal to 1, if there is no a surplus of electricity in r

and t after satisfying the needs plants with T2 technology
$W_{i,r,t}$ = amount of wastes i generated in region r in time period t

Appendix

For the subsystem Agriculture (oil palm growing), the process "Palm fruit bunch CO— production", allocation at point of substitution, is selected from Ecoinvent 3. Tables A1 shows a summary of the inputs and outputs for this subsystem. This process represents the production of palm fresh fruit bunches in Colombia. All the exchanges are based on field data from the main industrial oil palm cultivation area in Colombia, with an average annual yield of 18.3 t/ha. The inventory includes the use of fertilizers, pesticides, irrigation, and the field emissions from the fertilizer and pesticide application. This dataset also includes harvesting of palm fresh fruit bunches, land preparation and cultivation. Infrastructure processes are not taken into account for the calculation.

Table A1: Summary of the inputs and outputs for subsystem Agriculture per 1 t of FFB

	quantity	unit
Inputs		
Rain water	2260	mm/year
Land use	0,05	ha
P_2O_5	1,08	kg
K_2O	10,87	kg
S	0,48	kg
CaO	2	kg
MgO	2,4	kg
B_2O_3	0,4	kg
SiO_2	1,28	kg
Urea	1,47	kg
Ammonium nitrate	3,86	kg
Calcium nitrate	0,01	kg
Diammonium phosphate	0,01	kg
Monoammonium phosphate	0,2	kg
Ammonium sulfate	7,37	kg
B	0,05	kg
Zn	0,04	kg
Na	0,16	kg
Monosodium methanearsonate	0,18	kg
Glyphosate	0,67	kg
Diesel	4,65	kg
Gasoline	0,04	kg
Outputs		
FFB	1000	kg
Emissions to air		
Ammonia	604	kg
Dinitrogen monoxide	13	kg
Nitrogen oxides	3	kg
Emissions to water		
Nitrate (groundwater)	1845	kg
Phosphate (groundwater)	11	kg
Phosphorus (river)	172	kg
Emissions to soil		
Carbendazim	6	kg
Chromium	2	kg
Glyphosate	109	kg
Malathion	28	kg
Metalaxil	3	kg
Metam-sodium dihydrate	9	kg
Metsulfuron-methyl	7	kg
Paraquat	4	kg
Thiram	16	kg

Table A2: Summarizes the inputs and outputs for CPO production. Values are adapted from Ramirez-Contreras et al. (2020) T1 and T2 differ between them in the way that each technology groups solid waste and to then obtain electricity through technologies T6 and T7. T1 produces biomass 1 (fiber and shell) and T2 produces biomass2 (fiber, shell and EFB).

	quantity	unit
Inputs		
FFB	4683	kg
Water	2,59	m^3
Electricity	370,12	MJ
Diesel	0,49	L
Outputs		
CPO	1000	kg
Kernel	181	kg
Fiber and shell	835.6	kg
EFB	1050.8	kg
Emissions to air		
Ammonia	$3,90 \times 10^{-6}$	kg
Particulates, > 2.5 um, and < 10um	$2,93 \times 10^{-5}$	kg
Particulates, < 2.5 um	$5,54 \times 10^{-4}$	kg
Carbon dioxide, fossil	1,24	kg
Dinitrogen monoxide	$9,98 \times 10^{-6}$	kg
Methane	$4,33 \times 10^{-5}$	kg
Carbon monoxide	$1,91 \times 10^{-3}$	kg
Nitrogen oxides	$1,17 \times 10^{-2}$	kg
Non-methane volatile organic compounds (NMVOC)	$1,09 \times 10^{-3}$	kg

Table A3: summarizes the inputs and outputs for CPKO production. Values are mainly based on Subramaniam et al. (2010). Environmental burdens are allocated to the coproducts by mass content. This table does not report gate-to-gate emissions as the emissions due to processing itself are negligible.

	quantity	unit
Inputs		
Palm kernel	2083	kg
Electricity	465,3	MJ
Outputs		
CPKO	1000	kg
Cake	1120	kg

Table A4: Shows the inputs and outputs for biodiesel production. Values are mainly based on Wahyono et al. (2019). This table does not report gate-to-gate emissions as the emissions due to processing itself are considered negligible.

	quantity	unit
Inputs		
CPO	1090	kg
Water	1500	kg
Methanol	130	kg
Electricity	923,4	MJ
Sodium hydroxide	0,058	kg
Outputs		
Biodiesel	1000	kg
Glycerol	220	kg
Washing wastes	1500	kg

Table A5: Shows the inputs and outputs for refined oils according to (Yung, 2020)

	quantity	unit
Inputs		
CPO	1055	kg
Water	349,44	L
Electricity	923,4	MJ
Phosphoric acid	0,55	kg
Bleaching earth	11,05	kg
Natural gas	3,56	m^3
Diesel	0,33	kg
Fuel oil	0,74	kg
Inputs		
RPO1	800	kg
RPO2	200	kg
Waste water	40,06	L
Spent bleaching earth	11,09	kg
Emissions to air		
Ammonia	$3,30 \times 10^{-6}$	kg
Carbon dioxide, fossil	10,3	kg
Carbon monoxide, fossil	$6,86 \times 10^{-3}$	kg
Dinitrogen monoxide	$8,45 \times 10^{-6}$	kg
Formaldehyde	$4,28 \times 10^{-6}$	kg
Hydrogen chloride	$6,64 \times 10^{-5}$	kg
Methane, fossil	$3,13 \times 10^{-4}$	kg
Nitrogen oxides	$1,97 \times 10^{-2}$	kg
Non-methane volatile organic compounds (NMVOC)	$1,07 \times 10^{-3}$	kg
Particulates, < 2.5 um	$1,53 \times 10^{-3}$	kg
Particulates, > 2.5 um, and < 10um	$6,08 \times 10^{-4}$	kg
Particulates, > 10 um	$3,05 \times 10^{-4}$	kg
Sulfur dioxide	$2,48 \times 10^{-2}$	kg
Sulfur monoxide	$3,60 \times 10^{-5}$	kg
Volatile organic compounds (VOC)	$3,15 \times 10^{-4}$	kg

Table A6: Shows the exchanges for biomass-based electricity production (technologies T6 and T7). Data come from energy and mass balances, and emissions reported in Nasution et al. (2014)

	T6	T7	
	quantity		unit
Inputs			
Biomass 1 (fiber and shell)	200	-	kg
Biomass 2 (fiber, shell and EFB)	-	400	kg
Outputs			
Electricity	100	100	MJ
Emissions to air			
Ammonia	$7,64 \times 10^{-4}$		kg
Benzene	$4,02 \times 10^{-4}$		kg
Carbon monoxide, biogenic	$8,84 \times 10^{-2}$		kg
Dinitrogen monoxide	$1,02 \times 10^{-3}$		kg
Hydrocarbons, aliphatic, alkanes	$4,02 \times 10^{-4}$		kg
Hydrocarbons, aliphatic, unsaturated	$1,37 \times 10^{-3}$		kg
Methane, biogenic	$6,63 \times 10^{-4}$		kg
Nitrogen oxides	$6,63 \times 10^{-2}$		kg
Non-methane volatile organic compounds (NMVOC)	$1,55 \times 10^{-3}$		kg
Particulates, < 2.5 um	$1,10 \times 10^{-2}$		kg
Sulfur dioxide	$1,10 \times 10^{-3}$		kg

For transportation, the process “Transport, freight, lorry 7.5-16 metric ton, EURO3 {RoW} ” at the point of substitution, from Ecoinvent 3, is considered.

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Chapter 6

Conclusions and future work

6.1 Conclusions

This dissertation introduces the use of mathematical models to achieve an optimal design and planning of the palm oil (*Elaeis guineensis*) SC. The two models developed here are intended to be implemented in the Colombian palm oil industry as they are based on specific data about the logistic activities taking place in the production, processing, transportation, and final consumer demand stages of palm oil. Data were obtained from the main institutions involved in the Colombian palm oil industry. It is worth noting that the optimization models presented here are flexible enough to be adapted in other biomass-based products SCs, as well as in other contexts.

In this work, two models were developed for optimizing the palm oil SC in Colombia: a single-objective model that seeks to maximize the

NPV of the entire SC based only on economic criteria, and a multi-objective model that turns the first one into formulation model aimed at maximizing the SC profitability and minimizing its environmental impact at the same time. The estimation of the environmental impact objective is based on a single score ("eco-points"), which was used based on the implementation of the LCA methodology, which in turn ensures a holistic view of the environmental issues of the SC and is the state-of-the-art methodology in this regard. Structurally, both are MILP models and their linearity is maintained at all times to ensure the uniqueness of the optimal solutions in the single-objective model and in each Pareto solution (in the multi-objective model).

In the first model, based on an economic objective function, it becomes evident that longer planning horizons result in the investment distribution (installation of production and storage plants, and the purchase of vehicle) taking place in different years. On the contrary, in short time horizons, investment costs are incurred within the first year. These findings were obtained in the two demand scenarios (increasing and constant) that were considered. As the model is essentially budget driven, instead of being driven by the demand or the availability of raw materials, optimal networks tend to use all the available budget, which causes the investment costs to be very close in the short and the long term. Regarding operating costs, significant differences are observed in the two demand scenarios that were considered, as higher operating costs are obtained in the increasing demand scenario. In the case of transportation costs, they don't differ during the first years when different time horizons are used. However, as more years pass, transportation costs decrease in the growing demand scenario due to a reduction in the distribution channels (which in turn decreases the satisfaction of the demand in several regions of the country). With respect to the results obtained for different optimality gaps, a reconfiguration in the type and number of production plants is observed, but always showing a preference for CPO and biodiesel production plants, suggesting that the production actions carried out in these plants are the most profitable of the SC.

Regarding the MOO model (economic and environmental objective functions), this model provides Pareto optimal solutions evidencing the trade-off between economic and environmental objectives. The Pareto front showed that Pareto optimal solutions are practically ordered in a straight line, which indicates a virtually linear inverse relationship. That is, the greater the economic profit, the greater the environmental impact. It should be noted that these findings could be used in a future work to reformulate the optimization problem and decrease the computational cost by turning the model into a single-objective one) However, strictly speaking, there are very unnoticeable breakpoints in the Pareto front interrupting the linearity. Possibly, the structure of the model and the value of the parameters cause this behavior, which cannot be generalized without further study. When analyzed in detail, the Pareto front contains sections that select different technologies in the SC. Namely, to overcome a given value of the economic profit, the model prefers certain technologies over those it has been using, which leads to breakpoints in the Pareto front (it should be noted this was not the case in this case study). That is, after one of the Pareto points, the model increases the number of biodiesel production plants (due to their high profitability and lower environmental impact) and CPO production plants (raw material for biodiesel production) to be established at the expense of reducing the production of other products.

The results obtained using these two optimization models provide a valuable insight on the selection of manufacturing technologies for achieving new expansion policies. In addition, the Pareto optimal set helps decide what alternatives offer a reasonable balance between environmental and economic indicators. Given the current situation of the palm oil industry in Colombia, it is possible to conclude that both models are valuable tools to achieve a more rational distribution of production units when considering only economic aspects or both economic and environmental issues, as they were not considered when the palm oil SC currently in operation in Colombia was designed. The importance of planning using models that consider the current environmental and financial circumstances affecting the world as much as possible is reinforced by the fact that worldwide the palm oil industry is highly questioned because its social implications and the negative impact it has on human health and the environment. It is worth noting that the two models presented in this dissertation offer the possibility of generating electricity from the residual biomass of the palm oil SC. This approach allows obtaining solutions that reduce the waste volume of the SC and increase its energy sustainability from a circular economy perspective.

6.2 Future work

From a methodological point of view, two aspects of interest that are directly related with the results obtained in this dissertation have emerged during its development.

The first is the deeper study of the mathematical structure of the multi-objective model. This would allow the elucidation of (*i*) whether the inverse linear correlation obtained in the Pareto front is due to a per se formulation or to the particular case study and, (*ii*) if it is possible to decompose the model or to reduce the number of variables in order to decrease resource consumption while the model is executed.

The second is related to the uncertainty in the values of the parameters of the model, especially those associated with external uncertainty: unit costs, price of products, market demand for the products, etc. In this sense, the model can be easily adapted to a stochastic programming formulation, where uncertain parameters are represented by means of probability distributions. In such case, the aim of the model would be obtaining strong solutions that continue to be convenient despite the variation of the uncertain parameters.

From the perspective of the study cases, the interaction of the palm industry with other regional industries (e.g., the sugarcane industry) as a way to optimize the flow of resources between them (industrial symbiosis) is topic of interest that should be addressed in future works. Furthermore, the technology, final products and means of transportation options considered in both models could be increased, as long as the environmental and social aspects related to the development of the palm oil industry are always taken into account.

Appendix A

A.1 Publication

Peña González, D., Cortés Borda, D., Mele, F.D., Barrios Sarmiento, A., Domínguez Santiago, M., 2021. **An optimization approach for the design and planning of the oil palm supply chain in Colombia**. *Computers & Chemical Engineering* 146, 107208.

A.2 Paper under review

A multiobjective approach for the design and planning of more sustainable oil palm supply chains. Peña González, D., Machin Ferrero, L., Mele, F.D., Cortés Borda, D., Barrios Sarmiento, A., Domínguez Santiago, M. Paper submitted to the Journal of Cleaner Production on June 28, 2021.

A.3 Oral presentations

Peña González, D., Cortés Borda, D., Mele, F.D., Barrios Sarmiento, A., Domínguez Santiago, M. **Estrategia de optimización para el diseño de la cadena de suministros de la palma aceitera en Colombia**. II Congreso Internacional Virtual de Ingeniería Industrial: La industria y la ingeniería hacia una nueva normalidad. Colombia, Bogotá. 2020.

Peña González, D., Cortés Borda, D., Mele, F.D., Barrios Sarmiento, A., Domínguez Santiago, M. **Planificación óptima de la cadena de suministros de la palma aceitera en Colombia**. 4° congreso internacional de investigación multidisciplinaria. México, Ajalpan. 2021.

Peña González, D., Cortés Borda, D., Mele, F.D., Barrios Sarmiento, A., Domínguez Santiago, M. **Planeación estratégica de la Cadena de Suministros de la Palma Aceitera. Caso Colombia**. Colombia, Bogotá. 2021.

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