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PLANIFICACIÓN ÓPTIMA DE PRODUCCIÓN DE COMBUSTIBLES Y PLANTACIONES FORESTALES CONSIDERANDO EL ESQUEMA MULTI-STAKEHOLDER

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RESUMEN

PLANIFICACIÓN ÓPTIMA DE PRODUCCION DE COMBUSTIBLES Y PLANTACIONES FORESTALES CONSIDERANDO EL ESQUEMA MULTI-STAKEHOLDER

Por

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En este trabajo se proponen alternativas para mitigar el problema del cambio climático considerando la reducción de las emisiones de CO_2, entre estas alternativas se considera el uso de biocombustibles líquidos así como la implementación de plantaciones forestales integradas a la cadena de valor global asociada a combustibles fósiles. Por tal motivo, en este trabajo se propone integrar un sistema de producción de combustibles a través de refinerías y biorefinerías incluyendo el uso de plantaciones forestales para disminuir emisiones de gases de efecto invernadero mediante un modelo matemático para la planificación óptima de un sistema integrado de producción de combustibles y biocombustibles considerando la interacción con plantaciones forestales llamadas eco-industrias. Los resultados son obtenidos a través de un esquema tipo multi-stakeholder o múltiples tomadores de decisiones para considerar los beneficios y efectos de cada una de las entidades involucradas en la cadena de suministro y determinar las interacciones entre los diferentes entes involucrados para la toma de decisiones.

Palabras clave: Cadenas de suministro, Sistemas de energía, Multi-stakeholder, Planificación óptima, Captura de carbono.

ABSTRACT

This Thesis presents a mathematical programming model for the optimal planning of an integrated system for producing fuels and biofuels considering the interaction with facilities capable to capture emissions from biorefineries and refineries and receive a monetary benefit, these facilities can be named eco-industries or forest plantations. The proposed approach is formulated as a multi-stakeholder scheme to consider the benefits and affectations in each one of the involved supply chain entities, and determining how the interactions between the different stakeholders take place. This way, the proposed approach takes into account the profit of biorefineries, refineries and forest plantations, as well as the emissions and generated jobs of each one of the involved entities. Additionally, it is considered local and imported raw materials to satisfy the energy demand. Also, the approach considers features such as the project life time, the availability of resources, the amount and type of products that should be produced and the allocation and capacity of the refineries, biorefineries and forest plantations. The mathematical approach was applied to a nationwide case study for Mexico, considering the creation of new jobs, overall emissions and net profit as main objectives.

Keywords: Supply chains, Optimization, Multi-stakeholders, Strategic planning, Carbon capture.

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NOMENCLATURA

Parámetros no computados

w_i^{JF}	Factor de peso dado para el objetivo de empleos en eco-industrias.
w_i^{PR}	Factor de peso dado para el objetivo de ganancia en refinerías.
w_i^{PB}	Factor de peso dado para el objetivo de ganancia en biorefinerías.
w_i^{PF}	Factor de peso dado para el objetivo de ganancia en eco-industrias.
w_i^{ET}	Factor de peso dado para el objetivo de emisiones totales.
w_i^{JR}	Factor de peso dado para el objetivo de empleos en refinerías.
w_i^{JB}	Factor de peso dado para el objetivo de empleos en biorefinerías.

Parámetros computados

P^{L-R}	Límite mínimo obtenido para ganancia de refinerías.
P^{U-R}	Límite máximo obtenido para ganancia de refinerías.
P^{L-B}	Límite mínimo obtenido para ganancia de biorefinerías.
P^{U-B}	Límite máximo obtenido para ganancia de biorefinerías.
P^{L-F}	Límite mínimo obtenido para ganancia de eco-industrias.
P^{U-F}	Límite máximo obtenido para ganancia de eco-industrias.
E^{L-T}	Límite mínimo obtenido de emisiones totales.
E^{U-T}	Límite máximo obtenido de emisiones totales.
J^{L-R}	Límite mínimo obtenido para empleos generados en refinerías.
J^{U-R}	Límite máximo obtenido para empleos generados en refinerías.
J^{L-B}	Límite mínimo obtenido para empleos generados en biorefinerías.
J^{U-B}	Límite máximo obtenido para empleos generados en biorefinerías.
J^{L-F}	Límite mínimo obtenido para empleos generados en plantaciones forestales.
J^{U-F}	Límite máximo obtenido para empleos generados en plantaciones forestales.

Variables

CS_i	Solución Compromiso dada para cada caso de partes interesadas.
CS^*	Solución compromiso general.
P^R	Ganancia en refinerías.
P^B	Ganancia en biorefinerías.
P^F	Ganancia en Eco-industrias.
E^T	Emisiones totales.
J^R	Empleos en refinerías.
J^B	Empleos en biorefinerías.
J^F	Empleos en Eco-industrias.
DR	Relación de insatisfacción.
TJ	Empleos totales generados.
TP	Ganancias totales.

Índices

i Índices utilizados para denotar los casos de Stakeholders (partes interesadas) con diferentes prioridades.

Sets

I Set o conjunto que contiene todos los elementos del índice *i*.

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CAPÍTULO 1. INTRODUCCIÓN

1.1 Generalidades

De acuerdo al foro económico mundial, el consumo de energía fósil continúa en aumento desde el año 2012, pero a un ritmo menos acelerado que durante la última década, debido a que la energía renovable está tomando parte importante en la producción energética; el continuo incremento en la demanda de energía en el mundo es impulsado por el aumento poblacional y el crecimiento económico.

Dado que la globalización es un fenómeno impulsado por la tecnología y el movimiento de ideas, personas y bienes; hoy en día una nueva ola de dicha globalización está sobre nosotros, la denominada por el foro económico mundial como Globalización 4.0, donde la nueva frontera de globalización es el mundo cibernético y la economía digital que se está convirtiendo en una fuerza a considerar a través del comercio electrónico, los servicios digitales y la impresión 3D. Esto se ha incentivado por la inteligencia artificial, pero se encuentra amenazado y es vulnerable a la piratería y ataques cibernéticos transfronterizados.

Sin embargo, a través del efecto global del cambio climático, al mismo tiempo se está expandiendo una globalización negativa. Pues la contaminación en una parte del mundo conduce a fenómenos meteorológicos extremos en otra. Y la tala de bosques en los pocos “pulmones verdes” que el mundo ha dejado, como la selva amazónica, tiene efectos devastadores adicionales no solo en la biodiversidad, sino también en la capacidad para hacer frente a las peligrosas emisiones de gases de efecto invernadero.

Los cambios que se están dando hoy en día no son fenómenos aislados que afectan a un país, industria o problema en particular; son cambios mundiales, que requieren de una respuesta global y abordaje cooperativo que de no adoptarse representaría una tragedia para la humanidad. En específico, se requiere amplio compromiso e imaginación, donde será crucial el compromiso de todas las partes interesadas en un dialogo sostenido.

1.2 Justificación

Hoy en día la mayoría de los problemas sociales, políticos, económicos y organizacionales son problemas multi-stakeholder o de múltiples partes involucradas que toman decisiones independientes. Para estos problemas, ningún individuo o grupo tiene todas las respuestas, ya que puede haber múltiples “verdades” dependiendo de experiencias pasadas y la realidad actual. Por lo tanto, son necesarias diversas impresiones y puntos de vista alternativos. A medida que la toma de decisiones se vuelve más colectiva e inclusiva, la necesidad de enfoques participativos, colaborativos e integradores se vuelve más evidente y urgente.

La importancia de este trabajo es considerar múltiples objetivos basados en los tomadores de decisiones involucrados, la ventaja de esta metodología es que se pueden considerar tantos objetivos como se requiera evitando la complejidad de desarrollar conjuntos de Pareto que incrementa exponencialmente con respecto al número de objetivos.

1.3 Hipótesis

Mediante la aplicación de un enfoque multi-stakeholder en la solución de un modelo de optimización multi-objetivo, se obtendrá una planificación óptima del sistema de producción de combustibles e integración con plantaciones forestales, para satisfacer necesidades energéticas y capturar emisiones de CO_2.

1.4 Objetivo general

Desarrollar un modelo de optimización multi-objetivo empleando una metodología multi-stakeholder para la planificación sustentable del proceso de producción de combustibles líquidos en México considerando la distribución de plantaciones forestales en diferentes zonas de México para posibilitar la absorción de gases de efecto invernadero, principalmente CO_2.

1.5 Objetivos particulares

- Generar una metodología multi-stakeholder para aplicarla a un modelo de optimización multi-objetivo para la planificación óptima en la producción de combustibles en México.
- Considerar múltiples objetivos para el desarrollo de la metodología multi-stakeholder.
- Desarrollar una metodología capaz de proveer distintas soluciones para facilitar la toma de decisiones, en función de la ponderación de diferentes objetivos.
- Búsqueda de mejores soluciones para proveer la mayor satisfacción posible a cada parte involucrada.

CAPÍTULO 2. MARCO TEÓRICO

La Plataforma Mexicana de Carbono MÉXICO$_2$, describe un Sistema de Comercio de Emisiones (ETS, por sus siglas en inglés), como un mecanismo de intercambio de derechos de emisiones que sirve para controlar o fijar un límite de emisiones de gases de efecto invernadero (GEI) de empresas de diversos sectores de la economía, como generación de energía, transporte, refinación de petróleo, metalurgia cemento, papel, aviación, vidrio, cerámica, e industrias químicas y petroquímicas. Algunos ejemplos de estos mercados son el caso del Sistema de Comercio de Derechos de Emisión de la Unión Europea (UE) o el Mercado de Emisiones de California que es independiente a los demás estados de Estados Unidos de América (USA).

El régimen de comercio de derechos de emisión de la UE, es el principal mercado de carbono del mundo y el de mayor tamaño. Opera en los 28 países de la UE más Islandia, Liechtenstein y Noruega, cubriendo alrededor del 45% de las emisiones de gases de efecto invernadero de la UE.

En el caso del Mercado de Emisiones de California, este sistema de comercio de emisiones este sistema cubre el 85% del estado y dio inicio en 2013. En 2015 los sistemas de comercio de emisiones de California y Québec se interconectaron, formando un mercado común entre las dos jurisdicciones. Además California ofrece apoyo a otras jurisdicciones incluyendo acuerdos de alto perfil con México y China. En este marco las partes firmantes se comprometen a compartir información y lecciones aprendidas sobre las políticas climáticas con un enfoque especial en los sistemas de comercio de emisiones.

En México existe otro instrumento denominado Certificados de Energía Limpia (CELs) y que suele confundirse con el mercado de emisiones, sin embargo estos certificados funcionan como incentivos para que las empresas de generación de Energía generen electricidad a partir de fuentes de energía limpia como la energía geotérmica, eólica hidroeléctrica y solar, que no emiten gases de efecto invernadero o residuos peligrosos. El mercado de carbono se encuentra en fase de desarrollo en México a diferencia de los CELs que ya se encuentran implementados.

La diferencia entre ETS y los CELs radica principalmente en el hecho de que el mercado de emisiones busca fijar un límite al nivel de emisiones de GEI, mientras que los CELs incentivan la producción de energía a través de fuentes limpias y no contaminantes. Cada certificado representa la generación de 1 MWh de energía limpia, y su precio no es fijo pues depende la de oferta y demanda.

Los ETS regulan usualmente la emisión de CO_2 equivalente, es decir, cualquiera de los siguientes GEI: CO_2 (dióxido de carbono), CH_4 (metano), N_2O (óxido de nitrógeno), HFC (Hidrofluorocarbonos), y SF_6 (hexafluoruro de azufre). En un ETS existe un límite al volumen de emisiones de GEI que las empresas pueden emitir, así como un número limitado de derechos de emisión que se pueden otorgar y comercializar entre los participantes. El objetivo es que las empresas disminuyan gradualmente sus emisiones para cumplir con sus metas de reducciones de emisiones, muchas veces reflejadas en los Compromisos Nacionales de cada país, en el marco del Acuerdo de París. México se comprometió a reducir sus emisiones de GEI un 22% para 2030.

Además de los certificados de Energía Limpia y el mercado de emisiones, existen otros instrumentos a mencionar para no confundir con los anteriores. El mercado voluntario de carbono tiene características y funciones diferentes. Una reducción certificada de emisiones (a veces denominados “bono de carbono” u “*offset*”), es una forma de compensar la huella de carbono de una empresa. En este caso, la compensación de emisiones no es obligatoria, pero facilita el cumplimiento de metas autoimpuestas por las empresas. En este caso, las compañías pueden compensar comprando reducciones provenientes de proyectos certificados y registrados ante estándares internacionales. Algunos de los sectores que son grandes generadores de este tipo de proyectos son: reforestación, energías renovables, eficiencia energética y manejo de residuos. Una reducción certificada equivale a una tonelada de CO_2 equivalente que deja de emitirse la atmósfera. Por otra parte, es importante resaltar que una reducción de emisiones no es lo mismo que un bono verde, pues éste último es emisión de deuda financiera con la etiqueta verde, que se invierte para generar rendimientos.

Como se mencionó anteriormente, las reducciones de emisiones provienen de proyectos ambientales (implementados por empresas privadas en su gran mayoría); como son, parques eólicos, reforestación, estufas sustentables (instalación de dispositivos eficientes en comunidades cuyas estufas funcionan con leña, evitando enfermedades, tala de árboles y haciendo a la vez estufas más eficientes), rellenos sanitarios (utilización de biogás y producción de electricidad), etc. Para que un proyecto pueda obtener reducciones certificadas de emisiones, se debe certificar bajo estándares internacionales. Cuando se dice que una empresa, organización, individuo o institución compensó sus emisiones de GEI es porque compró reducciones de emisiones de algún proyecto. Por ejemplo, si una empresa quiere compensar las emisiones de una planta de producción por el lapso de un año, se hace el cálculo de emisiones y se compra el número equivalente de toneladas en bonos de carbono para compensar esa huella. Este mecanismo constituye el mercado voluntario de carbono. Las empresas participan de manera voluntaria para compensar sus emisiones.

México como parte del Acuerdo de París, enfocado a la lucha contra el cambio climático y cuyo objetivo es evitar que el incremento de la temperatura del mundo supere los 2°C para finales del siglo, se comprometió a que para el 2024 35% de la energía generada y consumida en el país será limpia. Para medir el cumplimiento de esta meta se crearon los Certificados de Energías Limpias, que acreditan que un porcentaje de la energía proviene de fuentes de energía limpia.

En México la Ley General de Cambio Climático 2012 y su reforma en 2018 tiene como objetivos, garantizar el derecho a un medio ambiente sano, regular las acciones para la mitigación y adaptación al cambio climático, fomentar la educación, investigación, desarrollo y transferencia de tecnología e innovación y difusión en materia de adaptación y mitigación al cambio climático y establecer la bases para la concertación con la sociedad.

2.1 Antecedentes

El fenómeno del incremento en la demanda energética y el aumento de la población están íntimamente relacionadas con el cambio climático. El calentamiento global, asociado a este cambio en el clima del planeta, es un serio problema que está provocando impactos alarmantes al entorno ambiental y humano, éste se debe principalmente a la generación de grandes cantidades de emisiones de gases de efecto invernadero como resultado, en su mayoría, de la quema de combustibles fósiles. Este no es un problema sencillo de resolver; sin embargo, se han llevado a cabo diversos esfuerzos para hacer frente al problema; por ejemplo, el uso de energía renovable o el uso de biomasa para producir biocombustibles.

Un gran número de investigadores han realizado diferente tipo de estudios para abordar este problema. En este sentido, Lundgren y col. (2015) expresan que es necesario limitar las emisiones de gases de efecto invernadero procedentes de actividades humanas. Yu y Zhu (2015) explican cómo limitar las emisiones de carbono en diferentes países y la competencia internacional por nuevas fuentes de energía, ya que la energía es fundamental para la prosperidad y la seguridad de las naciones. Varias alternativas han sido propuestas para abordar la problemática que se está viviendo en la actualidad. La política de impuestos al carbono se ha convertido en una forma efectiva de establecer límites de emisiones de carbono en muchos países, porque las emisiones de carbono significan costos adicionales para las industrias y, por lo tanto, tienen un impacto en las ganancias (Liu y col., 2016). Kober y col. (2016) investigaron las consecuencias macroeconómicas de la mitigación de emisiones de gases de efecto invernadero en américa latina. Vandyck y col. (2016) presentaron un modelo basado en los acuerdos de Paris, para evaluar las políticas de mitigación de las contribuciones previstas determinadas a nivel nacional, presentadas en el período previo a la COP21 por los estados miembros individuales, y una política para limitar el calentamiento global a 2°C por encima de los niveles preindustriales. Actualmente, la sustentabilidad y crecimiento económico limitan la agenda de discusión política internacional. Esto se debe principalmente a que existe una creciente preocupación por el cambio climático y, al mismo tiempo, los países buscan el crecimiento económico. En términos del cambio climático, la preocupación es que, asumiendo que la actividad humana continúa como está, el calentamiento global podría tener impactos adversos en la Tierra y en la economía global (Badau y col., 2016).

Otros autores han propuesto alternativas que involucran recursos de energía renovables. Por ejemplo, Hong y col. (2016) mencionaron que el uso de biocombustibles es una forma sustentable para satisfacer necesidades energéticas. También Ng y col. (2016) enunciaron que la biomasa es un potencial recurso de energía renovable para producir biocombustibles, químicos y otros productos de valor agregado utilizando varias tecnologías de procesamiento. En años recientes, la capacidad de producción de biogás se ha ampliado considerablemente en Alemania. Por ejemplo, Guenther-Lübbers y col. (2016) implementaron un estudio para proporcionar información acerca de los efectos positivos de la producción de biogás sobre aspectos socio-económicos de áreas rurales. Además, la utilización de CO_2 está ganando atención como una estrategia de reducción de gases de efecto invernadero complementaria al almacenamiento de CO_2 (Schakel y col., 2016). Además, Tapia y Tan (2014) declararon que la captura y almacenamiento de carbono es una forma importante de reducir las emisiones industriales. Adicionalmente, Brunori y col. (2017) estudiaron una plantación de robles como parte de una actividad centrada en la restauración de ecosistemas de un área donde se extrajo lignito desde 1863. Calcularon el carbono secuestrado por la biomasa de la plantación de robles, durante todo el ciclo de vida, y se midieron a través del Análisis del Ciclo de Vida, el impacto ambiental en términos de calentamiento global, demostrando que la plantación de árboles puede ser un importante sumidero de dióxido de carbono, especialmente si las especies seleccionadas tienen un nivel de crecimiento duradero y actividades de bajo impacto en la gestión de plantaciones.

Otros autores han propuesto el uso de programación matemática como alternativa para el diseño de esquemas que conduzcan a un mejor uso de la energía, diseñando diferentes tipos de cadenas de suministro y proponiendo metodologías de optimización. Por ejemplo, Grossmann (2002) proporcionó una revisión de las técnicas de programación mixta entera no lineal y disyuntiva, que son herramientas poderosas para resolver diversos problemas de optimización; esto es importante porque la mayoría de los problemas de planificación de la cadena de suministro y los problemas de ingeniería de sistemas de proceso utilizan algunas de estas técnicas para resolverlos. Por ejemplo, You y Grossmann (2008) propusieron una formulación matemática para la gestión del inventario en el diseño de cadenas de suministro, consideraron la minimización del costo ponderado del transporte, el establecimiento de las instalaciones y el costo de inventario. También, Hugo y Pistikopoulos (2005) presentaron una metodología basada en la programación matemática incluyendo la evaluación del ciclo de vida para el diseño y planificación de redes de cadenas de suministro utilizando optimización multi-objetivo. Además, Guillén-Gosálbez y Grossmann (2009) abordaron el diseño de cadenas de suministro de productos químicos sostenibles aplicando incertidumbre en el inventario del ciclo de vida vinculado a la operación de la cadena de suministro.

Además, Sánchez-Bautista y col. (2018) propusieron un enfoque de programación matemática para el diseño óptimo de la topología de una cadena de suministro para la producción de combustibles a través de refinerías y biorefinerías, integradas con plantaciones forestales enfocadas a la disminución de emisiones de gases de efecto invernadero, maximizando simultáneamente las ganancias totales del sistema y la generación de empleos, mostrando los resultados a través de una curva Pareto en tres dimensiones, donde se muestra sólo un conjunto de posibles soluciones. Sin embargo, las tres funciones objetivo se analizaron únicamente de forma global, por lo que es necesario hacer un análisis más profundo de sus efectos individuales al tomar en cuenta múltiples tomadores de decisiones.

El desarrollo de proyectos macro económicos de energía tiene inherentemente un conjunto de conflictos de interés. Primero, los inversionistas, que quieren asegurar el mejor desempeño económico del sistema. En seguida, las entidades políticas interesadas en el impacto social y ecológico de las nuevas instalaciones, así como en el desempeño económico. Finalmente, las comunidades locales consideran el impacto ambiental y los beneficios sociales de la implementación de proyectos tecnológicos (Vaissièree y col., 2017). Los enfoques multi-objetivo tradicionales consideran y limitan el problema para explorar el frente de Pareto y presentar las diferentes soluciones óptimas. El diseñador debe definir, de acuerdo con sus criterios particulares, una solución compromiso entre diferentes objetivos (Kou y col., 2014). Sin embargo, la presencia de múltiples participantes con diferentes objetivos, preferencias y criterios lleva a conflictos, que pueden afectar el desarrollo o la operación de nuevos proyectos (De Brucker y col., 2013). El principal problema es definir un marco de toma de decisiones de criterios múltiples que permita la negociación entre los participantes, reduciendo la brecha de información y creando un entorno de negociación para dialogar y alcanzar una solución compromiso (Ghodsi y col., 2016).

Cabe destacar que hoy en día la mayoría de los problemas sociales, políticos, económicos y organizacionales son problemas multi-stakeholder. Para estos problemas ningún individuo o grupo tiene todas las respuestas ya que puede haber múltiples “verdades” dependiendo de experiencias pasadas y la realidad actual. Por lo tanto, son necesarias diversas impresiones y puntos de vista alternativos. A medida que la toma de decisiones se vuelve más colectiva e inclusiva, la necesidad de enfoques participativos, colaborativos e integradores se vuelve más evidente y urgente. Este es el núcleo de la toma de decisiones de múltiples partes interesadas (Multi-Stakeholder Decision Making MSDM) que requiere nuevas perspectivas y principios para compromisos inclusivos de todos los participantes y que el compromiso debe dar lugar a un consenso y resultados ganar-ganar.

Por lo tanto, el marco de múltiples partes interesadas debe incluir, además de las soluciones óptimas, los efectos de utilizar los criterios particulares de los participantes en el proceso de toma de decisiones. De esta manera, cada una de las partes interesadas puede ser consciente de las consecuencias de usar sus criterios en la configuración final del sistema y las afectaciones inherentes en las soluciones propuestas por otras partes interesadas. Según Zavala y col. (2016), la generación de una curva de Pareto tiene dos inconvenientes importantes. La primera es que la decisión final es realizada por un solo tomador de decisiones, mientras que casi cualquier tarea involucra múltiples tomadores de decisiones. La segunda es que la complejidad de desarrollar un conjunto de Pareto es exponencial con respecto al número de objetivos. Además, Dowling y col. (2016) confirmaron que varios enfoques de optimización de objetivos múltiples tienen la dificultad de cuantificar qué tan satisfechos están los interesados con una decisión determinada y qué tan representativas son las opiniones de los interesados de la población en general. Por esa razón, Dowling y col. (2016) presentaron una metodología para abordar las prioridades de múltiples partes interesadas y múltiples objetivos sin el cálculo del conjunto completo de Pareto.

Un análisis interesante fue hecho por Marre y col. (2016), donde abordaron si la valoración económica de servicios de ecosistemas (ESV por sus siglas en inglés) es útil para los tomadores de decisiones o no, este análisis reveló la existencia de una brecha entre la teoría y la práctica en el uso de ESV. En teoría, la ESV se presenta y se percibe como una herramienta útil, pero en la práctica la ESV parece ser rara vez utilizada y tiene una influencia débil en la política. Este estudio es importante porque muestra la utilidad de este tipo de análisis para quienes toman decisiones.

Para incluir una estrategia de reducción de emisiones y una introducción sostenible de la producción de biocombustibles, este trabajo presenta un enfoque para producir biocombustibles y combustibles fósiles a través de biorefinerías y refinerías de petróleo con el objetivo de reducir emisiones de gases de efecto invernadero asociadas a la producción de combustibles con la integración de plantaciones forestales para captura de emisiones de CO_2. Es importante enfatizar que en este trabajo se evitan las desventajas de un método multi-objetivo generador como una curva de Pareto a través de un enfoque de múltiples partes interesadas que toma en cuenta la ganancia individual para cada entidad, las emisiones generadas y los empleos generados para cada entidad como un objetivo social.

Además, cabe señalar que varios trabajos han estudiado previamente problemas de múltiples partes interesadas; (ver Fuentes-Cortes y col. (2018a) y González-Bravo et al. (2017)). Por un lado, Fuentes-Cortes y col. (2018a) determinaron que los precios del carbono y el agua deben incrementarse en orden de magnitud de 2 a 3 para proporcionar un ingreso económicamente atractivo. Además, Fuentes-Cortes y col. (2018a) aplicaron la metodología a un sistema para planificar el uso de agua y energía, sin embargo, la topología del sistema se definió previamente. González-Bravo y col. (2017) aplicaron una metodología multi-stakeholder para el diseño de redes de distribución de energía y agua, su modelo es capaz de obtener la ubicación y el tamaño de las entidades involucradas en la red de agua Se debe tener en cuenta que los objetivos en esa metodología se consideran de manera general, es decir consideran un objetivo económico, uno ambiental y uno social.

Sin embargo, enfoques multi-stakeholder no han sido aplicados directamente a cadenas de suministro basadas en biomasa, ya que la mayoría de las metodologías han utilizado enfoques multi-objetivo considerando solo 1 a 3 objetivos. En este sentido, el enfoque actual tiene en cuenta diferentes objetivos para cada uno de los sistemas considerados en el sistema (biorefinerías, refinerías y plantaciones forestales). Vale la pena señalar que la configuración de la cadena de suministro afecta directamente el valor de los otros objetivos. Por ejemplo, si la cantidad de plantaciones forestales (en una configuración dada) incrementa, entonces las emisiones y ganancias de refinerías y biorefinerías disminuyen. Además, una diferencia importante con trabajos anteriores es que este trabajo propone un modelo de programación matemático sin una topología o configuración predefinida, ya que la interconexión entre los nodos de todas las cadenas de suministro consideradas (producción de combustible, producción de biocombustibles y eco-industrias) se obtiene cuando se resuelve el problema de optimización.

Adicionalmente, el esquema considerado en este trabajo toma en cuenta la interacción de diversos sistemas de producción tales como: producción de biocombustibles, producción de combustibles fósiles y forestación. Además, cada uno de los sistemas contabilizados está asociado a diferentes dimensiones de sustentabilidad como son: aspectos sociales, siendo en este caso empleos generados para plantaciones forestales y empleos generados para refinerías y biorefinerías; aspectos económicos, como las ganancias para biorefinerías, ganancias para refinerías y como aspecto ambiental las emisiones de CO_2.

En la **Figura 2.1** se muestra un panorama general del problema abordado, donde se presenta el objetivo del enfoque propuesto, que busca mejores soluciones para todas las partes involucradas y no solo una buena solución general que podría no ser suficientemente buena para algunos participantes.

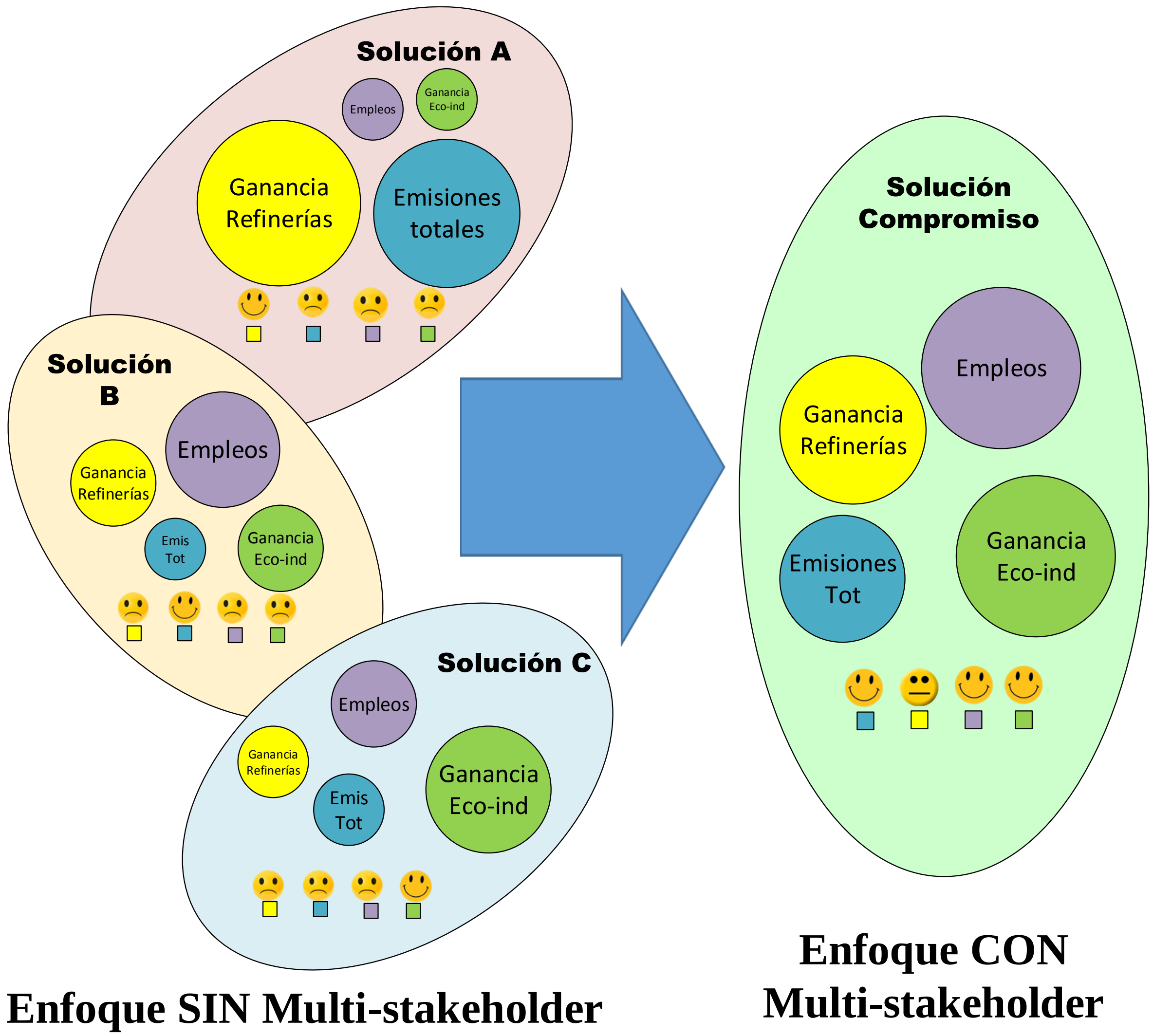

Figura 2.1 Representación general del problema abordado.

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CAPÍTULO 3. DESARROLLO DEL PROBLEMA

3.1 Definición del problema

El enfoque propuesto es una formulación de programación matemática para la planificación e integración óptimas de un sistema de producción de combustible considerando plantaciones forestales para captura de CO_2, bajo un esquema multi-stakeholder. Vale la pena recordar que un esquema multi-stakeholder implica múltiples tomadores de decisiones o múltiples partes interesadas y requiere nuevas perspectivas y principios para determinar los compromisos de todos los participantes y el compromiso debe dar lugar a un consenso y resultados en los que todos se vean beneficiados. El problema se puede definir en función de la superestructura representada en la **Figura 3.1**, y esto se explica a continuación:

Dados:

- Datos de localización potenciales para:
  - Proveedores de biomasa
  - Plantaciones forestales
  - Biorefinerías
  - Refinerías
- Costos asociados a la instalación y operación del sistema propuesto.

Entonces el problema consiste en determinar lo siguiente:

- El tamaño y localización de las instalaciones (proveedoras de biomasa, pozos petroleros, refinerías, biorefinerías y plantaciones forestales.
- La interconexión entre ellas.
- Cantidad de materia prima consumida (biomasa y petróleo).
- El número de empleos generados por la cadena de suministro integrada.

Además, el modelo propuesto incorpora conceptos de intercambio de contaminantes, para reducir emisiones a través de plantaciones forestales con diferente capacidad y tamaño. Debe notarse que la demanda de combustible, se puede satisfacer vía combustible fósil o biocombustible, y se recibe de diferentes centros de distribución. Finalmente, el modelo se resuelve a través del enfoque multi-stakeholder, que involucra resolver el problema maximizando un conjunto de funciones objetivo ponderadas asociadas a diferentes prioridades para cada tomador de decisiones.

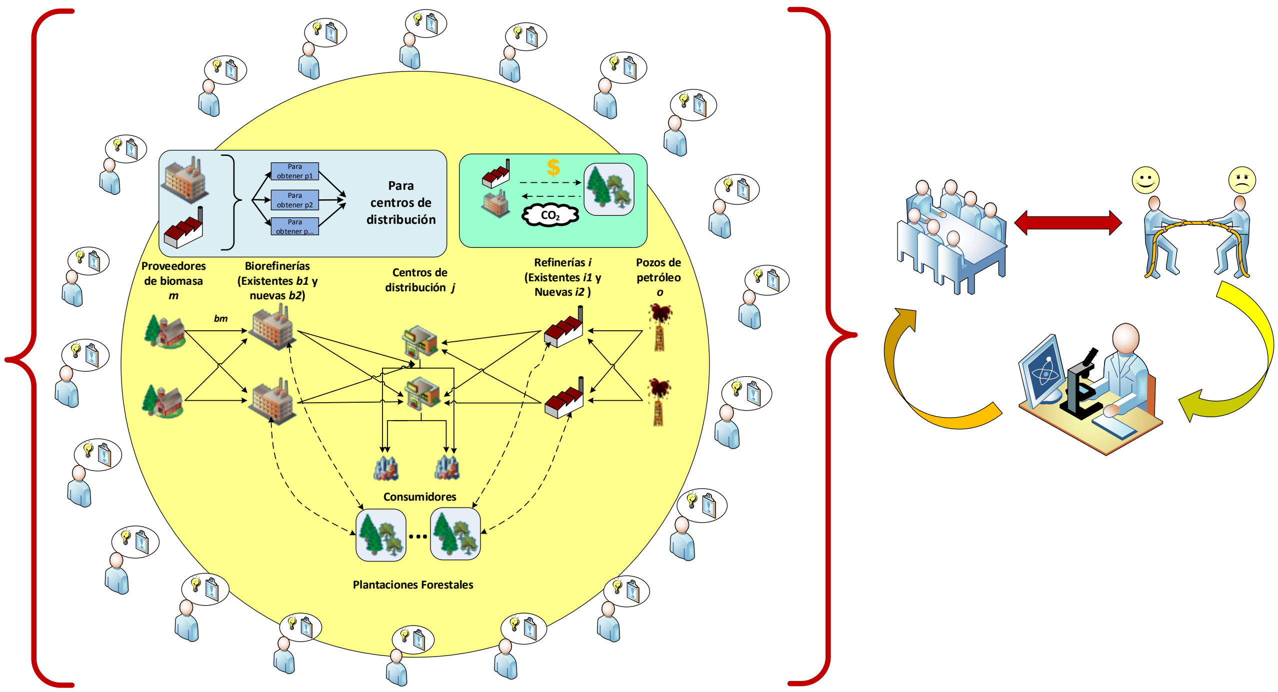

Figura 3.1 Superestructura del problema de integración de biorefinerías, refinerías y plantaciones forestales considerando multi-stakeholder.

3.2 Metodología

3.2.1 Formulación del modelo matemático

A partir del modelo de optimización reportado por Sánchez-Bautista et al. (2017), se realizaron adecuaciones y se agregaron algunas ecuaciones para considerar el esquema de multi-stakeholder, estas modificaciones están relacionadas con las funciones objetivo para poder realizar un análisis de los casos cuando se obtienen valores óptimos de la ganancia para cada refinería, biorefinería y eco-industria; así como el número de empleos.

A partir de una ecuación para ganancias totales de refinerías, se requirió obtener dos ecuaciones para calcular las ganancias individuales de cada refinería, una para refinerías existentes y otra para refinerías nuevas, estas ecuaciones se muestran a continuación:

$$\begin{aligned} Profit^{Refinery} = {} & \sum_{i} Revenue_{i}^{sold-product-ref} - \sum_{i} Cost_{i}^{oil} - \sum_{i} C_{i}^{opRef} - \sum_{i2} C_{i2}^{CapRef} - \sum_{i1} C_{i1}^{Trans-oil-exis} \\ & - \sum_{i1} C_{i1}^{Trans-products-ref-exis} - \sum_{i2} C_{i2}^{Trans-oil-new} - \sum_{i2} C_{i2}^{Trans-products-ref-new} \\ & - \sum_{i} \mathrm{CEmis}_{\mathrm{i}}^{\mathrm{Ref}} \cdot Emcap_{i}^{Refinery} \end{aligned} \quad (1)$$

$$\begin{aligned} Profit_{i1}^{Refineryindi} = {} & Revenue_{i1}^{sold-product-ref} - Cost_{i1}^{oil} - C_{i1}^{opRef} - C_{i1}^{Trans-oil-exis} \\ & - C_{i1}^{Trans-products-ref-exis} - \mathrm{CEmis}_{\mathrm{i1}}^{\mathrm{Ref}} \cdot Emcap_{i1}^{Refinery} \end{aligned} \quad (1a)$$

$$\begin{aligned} Profit_{i2}^{Refineryindi} = {} & Revenue_{i2}^{sold-product-ref} - Cost_{i2}^{oil} - C_{i2}^{opRef} - C_{i2}^{CapRef} - C_{i2}^{Trans-oil-new} \\ & - C_{i2}^{Trans-products-ref-new} - \mathrm{CEmis}_{\mathrm{i2}}^{\mathrm{Ref}} \cdot Emcap_{i2}^{Refinery} \end{aligned} \quad (1b)$$

Para el caso de la ecuación que representa las ganancias totales de biorefinerías, se obtuvo a partir de ella dos ecuaciones para obtener la ganancia individual de cada biorefinería:

$$\begin{aligned} Profit^{Bioref} = {} & \sum_{b} Revenue_{b}^{sold-prod-bioref} - \sum_{b} Cost_{b}^{Biomass-Growth} - \sum_{b2} C_{b2}^{CapBioref} - \sum_{b} C_{b}^{opBioref} \\ & - \sum_{b1} C_{b1}^{Trans-biomass-exis} - \sum_{b1} C_{b1}^{Trans-product-bioref-exis} - \sum_{b2} C_{b2}^{Trans-biomass-new} \\ & - \sum_{b2} C_{b2}^{Trans-product-bioref-new} - \sum_{b} \mathrm{CEmis}_{\mathrm{b}}^{\mathrm{Bioref}} \cdot Emcap_{b}^{Biorefinery} \end{aligned} \quad (2)$$

$$Profit_{b1}^{Biorefindi} = Revenue_{b1}^{sold-prod-bioref} - Cost_{b1}^{Biomass-Growth} - C_{b1}^{opBioref} - C_{b1}^{Trans-biomass-exis} - C_{b1}^{Trans-product-bioref-exis} - \mathrm{CEmis}_{\mathrm{b1}}^{\mathrm{Bioref}} \cdot Emcap_{b1}^{Biorefinery} \tag{2a}$$

$$Profit_{b2}^{Biorefindi} = Revenue_{b2}^{sold-prod-bioref} - Cost_{b2}^{Biomass-Growth} - C_{b2}^{opBioref} - C_{b2}^{CapBioref} - C_{b2}^{Trans-biomass-new} - C_{b2}^{Trans-product-bioref-new} - \mathrm{CEmis}_{\mathrm{b1}}^{\mathrm{Bioref}} \cdot Emcap_{b1}^{Biorefinery} \tag{2b}$$

Para eco-industrias se hicieron variaciones para obtener la ganancia individual de cada una, se cambió la ecuación que calculaba la ganancia total de eco-industrias y las ecuaciones para calcular las emisiones capturadas a las refinerías y biorefinerías, quedando otra ecuación para calcular las ganancias totales de las eco-industrias. A continuación se muestran las ecuaciones obtenidas:

$$Profit_{e}^{Ecoindindi} = \sum_{i} \mathrm{CEmis}_{\mathrm{i}}^{\mathrm{Ref}} \cdot Emcap_{i,e}^{Refinery\_Eco} + \sum_{b} CEmis_{b}^{Bioref} \cdot Emcap_{b,e}^{Biorefinery\_Eco} - C_{e}^{TotalEcoind} \tag{3}$$

$$Emcap_{i}^{Refinery} = \sum_{e} Emcap_{i,e}^{Refinery\_Eco} \tag{4}$$

$$Emcap_{b}^{Bioefinery} = \sum_{e} Emcap_{b,e}^{Biorefinery\_Eco} \tag{5}$$

$$Profit^{Ecoind} = \sum_{e} Profit_{e}^{Ecoindindi} \tag{6}$$

En caso de las ecuaciones para calcular empleos, se transformaron para obtener los empleos individuales para cada una de las refinerías, biorefinerías y eco-industrias:

$$Jobs^{Refinery} = \mathrm{H_Y} \cdot \sum_{i2} \mathrm{JobsUnit}_{\mathrm{i2}}^{\mathrm{ref}} \cdot \left(f_{i2}^{oil} \right) \tag{7}$$

$$Jobs_{i2}^{Refindiv} = \mathrm{H_Y} \cdot \mathrm{JobsUnit}_{\mathrm{i2}}^{\mathrm{ref}} \cdot \left(f_{i2}^{oil} \right) \tag{8}$$

$$Jobs^{Bioref} = \mathrm{H_Y} \cdot \sum_{bm,m} \mathrm{JobsUnit}_{\mathrm{bm,m}}^{\mathrm{biomplat}} \cdot F_{bm,m}^{Biomass-field} + \mathrm{H_Y} \cdot \sum_{bm,m,b} \mathrm{JobsUnit}_{\mathrm{bm,m,b}}^{\mathrm{biomtransp}} \cdot f_{bm,m,b}^{Biomass1} + \mathrm{H_Y} \cdot \sum_{bm,b} \mathrm{JobsUnit}_{\mathrm{bm,b}}^{\mathrm{biombioref}} \cdot F_{bm,b}^{Biomass} \tag{9}$$

$$Jobs_{b}^{Biorefindiv} = \mathrm{H_Y} \cdot \sum_{bm,m} \mathrm{JobsUnit}_{\mathrm{bm,m}}^{\mathrm{biomplat}} \cdot f_{bm,m,b}^{Biomass1} + \mathrm{H_Y} \cdot \sum_{bm,m} \mathrm{JobsUnit}_{\mathrm{bm,m,b}}^{\mathrm{biomtransp}} \cdot f_{bm,m,b}^{Biomass1} + \mathrm{H_Y} \cdot \sum_{bm} \mathrm{JobsUnit}_{\mathrm{bm,b}}^{\mathrm{biombioref}} \cdot F_{bm,b}^{Biomass} \qquad (10)$$

$$Jobs^{Ecoind} = \sum_{e} \mathrm{JobsUnit}_{\mathrm{e}}^{\mathrm{Ecoind}} \cdot \mathrm{NT_e} \qquad (11)$$

$$Jobs_{e}^{Ecoindindiv} = \mathrm{JobsUnit}_{\mathrm{e}}^{\mathrm{Ecoind}} \cdot \mathrm{NT_e} \qquad (12)$$

El modelo matemático considera integración entre biorefinerías y refinerías con plantaciones forestales denominadas Eco-industrias, con el objetivo de obtener emisiones totales, empleos y ganancias para cada una de las instalaciones consideradas. El enfoque matemático consiste en balances de masa entre las diferentes entidades de la cadena de suministro, restricciones técnicas y económicas, y funciones para evaluar el desempeño del sistema, como la ganancia total anual, número de empleos generados y emisiones netas, las cuales se describen en el artículo publicado por Sánchez-Bautista et al. (2017) que se presenta en el apéndice A. La formulación del modelo se mejoró para incluir una función ponderada para tener en cuenta la diferente importancia dada para cada una de las partes interesadas involucradas, que se muestra en la Ecuación 13. Esta función convierte el problema multi-objetivo original en un modelo de optimización de un solo objetivo, donde la función objetivo es una función ponderada conocida como Solución Compromiso. La Ecuación 13 establece que la función compromiso es igual a la suma de un peso significativo multiplicado por una función normalizada para cada una de las funciones objetivo.

$$CS_i = \begin{array}{l} w_i^{PR} \cdot \dfrac{P^R - \mathrm{P^{L\text{-}R}}}{\mathrm{P^{U\text{-}R}} - \mathrm{P^{L\text{-}R}}} + w_i^{PB} \cdot \dfrac{P^B - \mathrm{P^{L\text{-}B}}}{\mathrm{P^{U\text{-}B}} - \mathrm{P^{L\text{-}B}}} + w_i^{PF} \cdot \dfrac{P^F - \mathrm{P^{L\text{-}F}}}{\mathrm{P^{U\text{-}F}} - \mathrm{P^{L\text{-}F}}} + w_i^{ET} \cdot \dfrac{\mathrm{E^{U\text{-}T}} - E^T}{\mathrm{E^{U\text{-}T}} - \mathrm{E^{L\text{-}T}}} \\ + w_i^{JR} \cdot \dfrac{J^R - \mathrm{J^{L\text{-}R}}}{\mathrm{J^{U\text{-}R}} - \mathrm{J^{L\text{-}R}}} + w_i^{JB} \cdot \dfrac{J^B - \mathrm{J^{L\text{-}B}}}{\mathrm{J^{U\text{-}B}} - \mathrm{J^{L\text{-}B}}} + w_i^{JF} \cdot \dfrac{J^F - \mathrm{J^{L\text{-}F}}}{\mathrm{J^{U\text{-}F}} - \mathrm{J^{L\text{-}F}}} \end{array}, \ \forall i \in I \qquad (13)$$

Es importante resaltar que los pesos (w_i^{PR}, w_i^{PR}, w_i^{PR}, w_i^{PR}, w_i^{PR}, w_i^{PR} y w_i^{PR}) representan el factor de importancia para cada una de las funciones de interés, las cuales son, ganancia de refinerías (P^R), ganancia de biorefinerías (P^B), ganancia de plantaciones forestales (P^F), emisiones totales (E^T), empleos generados por refinerías (J^R), empleos generados por biorefinerías (J^B) y empleos generados por plantaciones forestales (J^F). Representan el nivel de preferencia de cada Stakeholder con respecto a las funciones objetivo de acuerdo con los criterios individuales ($0 \le w \le 1$). De esta manera, esta formulación permite a cada Stakeholder definir sus prioridades sobre el desempeño del sistema. Los parámetros con superíndices U y L son los limites máximo y mínimo para las funciones, respectivamente. Estos parámetros se obtienen por la maximización y minimización de las funciones individuales, es decir, sin tomar en cuenta otras. Además, estos parámetros definen el punto Utópico (UP) y el punto Nadir (NP).

El esquema multi-stakeholder está basado en la maximización de la solución compromiso (CS_i) para todos los Stakeholders (*i*). Esta etapa produce una solución óptima para cada tomador de decisiones, pero soluciones sub-óptimas para los demás. Adicionalmente, es posible obtener una solución compromiso general. Para este caso, la solución compromiso es igual al promedio de todas las soluciones compromiso óptimas individuales de cada tomador de decisiones. Esto se obtiene minimizando el valor absoluto de la diferencia entre la solución deseada de cada stakeholder y la solución compromiso a encontrar. Esto se muestra en la Ecuación 14.

$$Min\left\{ABS\left[CS^* - \left(1/I\right)\cdot\sum_i CS_i\right]\right\} \tag{14}$$

Se puede notar que la Ec. (14) no es una función continua; por lo tanto, esta función fue discretizada en dos casos. El primer caso es cuando la diferencia entre la solución compromiso deseada es negativa y el segundo caso es cuando la diferencia es positiva.

La disyunción asociada se muestra a continuación:

$$\begin{bmatrix} Y1 \\ CS^* \ge \left(1/I\right)\sum_i CS_i \\ ABS = CS^* - \left(1/I\right)\sum_i CS_i \end{bmatrix} \vee \begin{bmatrix} Y2 \\ CS^* \le \left(1/I\right)\sum_i CS_i \\ ABS = \left(1/I\right)\sum_i CS_i - CS^* \end{bmatrix}$$

La disyunción previa se reformula por medio de la metodología Convex Hull. En este sentido, sólo una variable binaria se puede activar; por lo tanto, la suma de las variables binarias debe ser igual a uno.

$$y1 + y2 = 1 \qquad (15)$$

Además, cada variable continua en la disyunción debe ser expresada como function de las variables desagregadas:

$$ABS = abs1 + abs2 \qquad (16)$$

$$CS^{*} = CS1^{*} + CS2^{*} \qquad (17)$$

Tambien, las variables desagregadas estan establecidas de acuerdo con cada parte de la disyunción y limitadas por las variables binarias:

$$abs1 = CS1^{*} - \left(1/I \right) \cdot y1 \cdot \sum_{i} CS_{i} \qquad (18)$$

$$abs2 = \left(1/I \right) \cdot y2 \cdot \sum_{i} CS_{i} - CS2^{*} \qquad (19)$$

Además, las ecuaciones 18 y 19 son utilizadas para activar las variables binarias, ya que la variable binaria ($y1$) es igual a 1 cuando ($CS1^{*}$) es mayor que la función compromiso promedio; mientras que la variable binaria ($y2$) es igual a 1 cuando ($CS2^{*}$) es menor que la función compromiso promedio.

$$CS1^{*} \geq \left(1/I \right) \cdot y1 \cdot \sum_{i} CS_{i} \qquad (20)$$

$$CS2^{*} \leq \left(1/I \right) \cdot y2 \cdot \sum_{i} CS_{i} \qquad (21)$$

Así mismo, las variables desagregadas están limitadas a asegurar que si la variable binaria es activada, entonces las variables desagregadas son igual a cero, por lo tanto su contribución a la variable total correspondiente es igual a cero.

$$CS1^{*} \leq CS^{\max} \cdot y1 \qquad (22)$$

Como se puede ver, la función discontinua, que es la que tiene el valor absoluto, es transformada a un Problema de Optimización Mixto Entero Lineal (MILP); que se puede resolver a través de cualquier resolvedor de optimización como CPLEX.

También, la relación de insatisfacción para cada tomador de decisiones puede ser calculada, y está relacionada a la diferencia entre la solución compromiso final y la solución compromiso para cada stakeholder, como se muestra a continuación:

$$Dissatisfaction-relation_i = DR = ABS\left(\frac{CS^{*} - CS_i}{CS_i}\right), \ \forall i \in I \qquad (23)$$

Finalmente, para analizar el comportamiento económico, ambiental y social, las funciones objetivo individuales se concentran en funciones objetivo principales, siendo por lo tanto, la ganancia total, emisiones totales, y empleos totales generados. Estas funciones agrupadas son importantes para representar el sistema de una manera general. El total de trabajos y el beneficio total se indican a continuación:

$$TotalProfit = TP = P^{R} + P^{B} + P^{F} \qquad (24)$$

$$TotalJobs = TJ = J^{R} + J^{B} + J^{F} \qquad (25)$$

La propuesta para solucionar el problema de optimización multi-objetivo con el enfoque multi-stakeholder es la siguiente:

La solución del problema considera criterios en conflicto. Por lo tanto, el enfoque multi-stakeholder para toma de decisiones trata de identificar la solución ideal y la peor solución, y con ello asociar compensaciones para el sistema, buscando tomar una decisión final que alcance una forma de consenso o solución de compromiso (Fuentes-Cortes y col., 2018b).

Para resolver el problema, primero se establecen siete funciones objetivo: Ganancias para refinerías, biorefinerías y plantaciones forestales, emisiones netas totales, empleos generados para refinerías, biorefinerías y plantaciones forestales. Luego, es necesario maximizar y / o minimizar cada función objetivo para determinar los límites inferior y superior para cada una de las funciones objetivo, estas soluciones definen las coordenadas del Punto Utópico y Punto Nadir.

La solución del punto utópico se obtiene a través de la "mejor solución" para cada objetivo (valor máximo para ganancias y empleos, y valor mínimo para emisiones netas totales). El punto utópico no es implementable, ya que los objetivos son conflictivos, pero se utiliza como una referencia ideal. La solución nadir (NS) se obtiene a través de los valores del peor caso para los objetivos en el punto utópico. Por ejemplo, cuando se maximizan las ganancias y los empleos de las refinerías individualmente, se obtiene el peor valor de las emisiones. Esto muestra implícitamente la compensación entre objetivos (Fuentes-Cortes y col., 2018b). Luego, se establecen pesos para ponderar y reflejar las prioridades de los diferentes tomadores de decisiones para calcular la solución compromiso para cada parte interesada. Finalmente, se obtiene una solución compromiso global y la relación de insatisfacción de los interesados.

3.2.2 Solución del modelo para un caso de estudio

El enfoque matemático propuesto se aplicó a un caso de estudio para México, se consideraron seis refinerías existentes en México y tres localizaciones potenciales para instalación de refinerías adicionales, esto basado en demanda de productos y en la infraestructura para transporte de materias primas y productos. En lo que se refiere a biorefinerías, se consideró la posibilidad de instalar seis, debido a que actualmente no hay ninguna en el país. En cuanto a Eco-industrias (plantaciones forestales), se considera cada estado para instalar, pero se limita por la disponibilidad de tierra así como por condiciones climáticas.

Respecto a materias primas para biorefinerías, se consideraron diferentes tipos de biomasa incluidas caña de azúcar, sorgo dulce, astillas de madera, palma africana, jatropha y residuos de agave. También, el caso de estudio considera proveedores de biomasa por casa estado, sin embargo, cada proveedor de biomasa contiene disponibilidad de biomasa diferente según datos de Estadística de la Producción Agrícola de SAGARPA. Así mismo, de acuerdo con Petróleos Mexicanos (PEMEX), las zonas de pozos petroleros que se tomaron en cuenta para extracción de petróleo son: Aguas territoriales, Tabasco, Veracruz, Chiapas, Puebla, Tamaulipas y San Luis Potosí. Además, se consideraron 45 centros correspondientes a terminales de almacenamiento y distribución de PEMEX localizadas dentro de territorio mexicano.

Vale la pena señalar que el modelo matemático es general y se puede aplicar a otros casos de estudio, siempre y cuando se consideren los datos específicos. Los parámetros requeridos se enumeran en la sección de nomenclatura como "Parámetros no computados", mientras que los parámetros computados a través del problema de optimización individual (para obtener límites para calcular otras variables) se pueden calcular a partir del modelo. Los datos necesarios para el caso de estudio se presentan en apéndice A en el artículo publicado por Sánchez-Bautista et al. (2017).

CAPÍTULO 4. RESULTADOS

El modelo de optimización es un problema multi-objetivo mixto-entero lineal. Dicho modelo consta de 6,407 variables continuas, 2,161 variables vinarias y 5,431 restricciones. El modelo fue codificado en software GAMS. Este modelo se resolvió utilizando el resolvedor CPLEX en una computadora con procesador Intel Core i7, procesador de 2.90 GHz y 16 GB de RAM. El tiempo de CPU promedio para cada solución del modelo matemático fue alrededor de 0.156s.

El enfoque multi-stakeholder consideró 20 partes interesadas individuales, que están asociadas a diversos factores de ponderación. Los pesos utilizados representan las preferencias y los criterios de los participantes. Como se observa, la complejidad del problema aumenta a medida que se agregan más participantes con diferentes criterios y prioridades al entorno de toma de decisiones de múltiples criterios. Se han presentado un conjunto de criterios representativos para el problema, evitando la inclusión de partes interesadas que pueden usar niveles de preferencia similares. Obviamente, la formulación utilizada permite incluir partes interesadas con el mismo nivel de prioridades en las funciones objetivo. La **Tabla 4.1** resume el valor de los factores de ponderación, las soluciones compromiso para cada uno de ellos y el índice de insatisfacción para cada caso. La **Tabla 4.2** presenta los valores de las funciones objetivos concentradas. Es importante tener en cuenta que el valor de insatisfacción se obtiene para cada una de las partes interesadas con respecto a la solución compromiso, que es la solución sin considerar pesos en las funciones objetivo.

De acuerdo con las **Tablas 4.1** y **4.2**, el caso con mayor relación de insatisfacción es el Caso 14 con 6.10, en este caso se desatienden los objetivos asociados a biorefinerías y refinerías (ganancias y empleos). Es decir, los objetivos relacionados con las plantaciones forestales tienen más peso. Además, se puede observar que el número de empleos totales es uno de los valores más bajos para las soluciones restantes. Además, hay varios casos con bajas relaciones de insatisfacción, uno de ellos es el caso 11, cuyos objetivos relacionados con las plantaciones forestales están ponderados. En el caso 11, la cantidad de empleos se mejoró significativamente a 3.08 millones de nuevos empleos, mientras que la ganancia se redujo de \$US $2.66x10^{10}$ a \$US $2.03 x10^{10}$ con respecto al Caso 14.

Tabla 4.1 Resumen de factores de ponderación o pesos, solución compromiso (CS_i) y relación de insatisfacción (DR) para cada caso.

Caso	w_i^{PR}	w_i^{PB}	w_i^{PF}	w_i^{ET}	w_i^{JR}	w_i^{JB}	w_i^{JF}	CS_i	DR
1	1	0	0	0	0	0	0	0.99	0.70
2	0	1	0	0	0	0	0	1.00	0.69
3	0	0	1	0	0	0	0	1.00	0.69
4	0	0	0	1	0	0	0	1.00	0.69
5	0	0	0	0	1	0	0	1.00	0.69
6	0	0	0	0	0	1	0	1.00	0.69
7	0	0	0	0	0	0	1	1.00	0.69
8	1/7	1/7	1/7	1/7	1/7	1/7	1/7	0.78	1.17
9	1/2	0	0	0	1/2	0	0	0.99	0.70
10	0	1/2	0	0	0	1/2	0	0.66	1.55
11	0	0	1/2	0	0	0	1/2	1.00	0.69
12	1/3	0	0	1/3	1/3	0	0	0.87	0.94
13	0	1/3	0	1/3	0	1/3	0	0.76	1.21
14	0	0	1/3	1/3	0	0	1/3	0.24	6.10
15	1/4	1/4	0	0	1/4	1/4	0	0.82	1.06
16	1/4	0	1/4	0	1/4	0	1/4	0.79	1.14
17	0	1/4	1/4	0	0	1/4	1/4	0.83	1.03
18	1/5	1/5	0	1/5	1/5	1/5	0	0.79	1.14
19	1/5	0	1/5	1/5	1/5	0	1/5	0.54	2.11
20	0	1/5	1/5	1/5	0	1/5	1/5	0.86	0.96

Tabla 4.2 Valores de funciones objetivo concentradas para cada caso.

Caso	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
TP x10^{-10}	2.78	2.56	2.03	2.13	2.28	2.53	2.03	2.16	2.71	2.69
E^T x10^{-10}	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73
TJ x10^{6}	0.03	0.03	3.08	3.08	0.04	0.04	3.08	3.09	0.04	0.03
Caso	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
TP x10^{-10}	2.03	2.64	2.16	2.66	2.67	2.16	1.69	2.67	2.67	2.16
E^T x10^{-10}	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73
TJ x10^{6}	3.08	0.04	3.07	0.03	0.05	3.08	3.09	0.05	0.04	3.09

La **Figura 4.1** muestra diversos puntos, donde el beneficio total y los empleos generados se maximizan, mientras que las emisiones se minimizan, también esta figura muestra los puntos de la solución utópica, la solución nadir y la solución compromiso. El punto A no considera los objetivos ambientales y sociales, representa la solución de máxima ganancia, este punto podría ser un punto factible; sin embargo, los objetivos de emisiones y la cantidad de empleos están lejos de sus mejores valores. Además, este punto es el más cercano a la solución compromiso, pero se aleja de la solución utópica con respecto al número de empleos. El punto B no considera los objetivos económicos y sociales, representa la solución con las emisiones más bajas y el punto C viene dado por la solución del número máximo de empleos sin tener en cuenta los otros objetivos. El punto utópico denota la mejor solución, aunque esta solución no es factible y ya está representada por la máxima ganancia total, el número máximo de empleos y la mínima cantidad de emisiones, por lo que no es posible implementar esta solución.

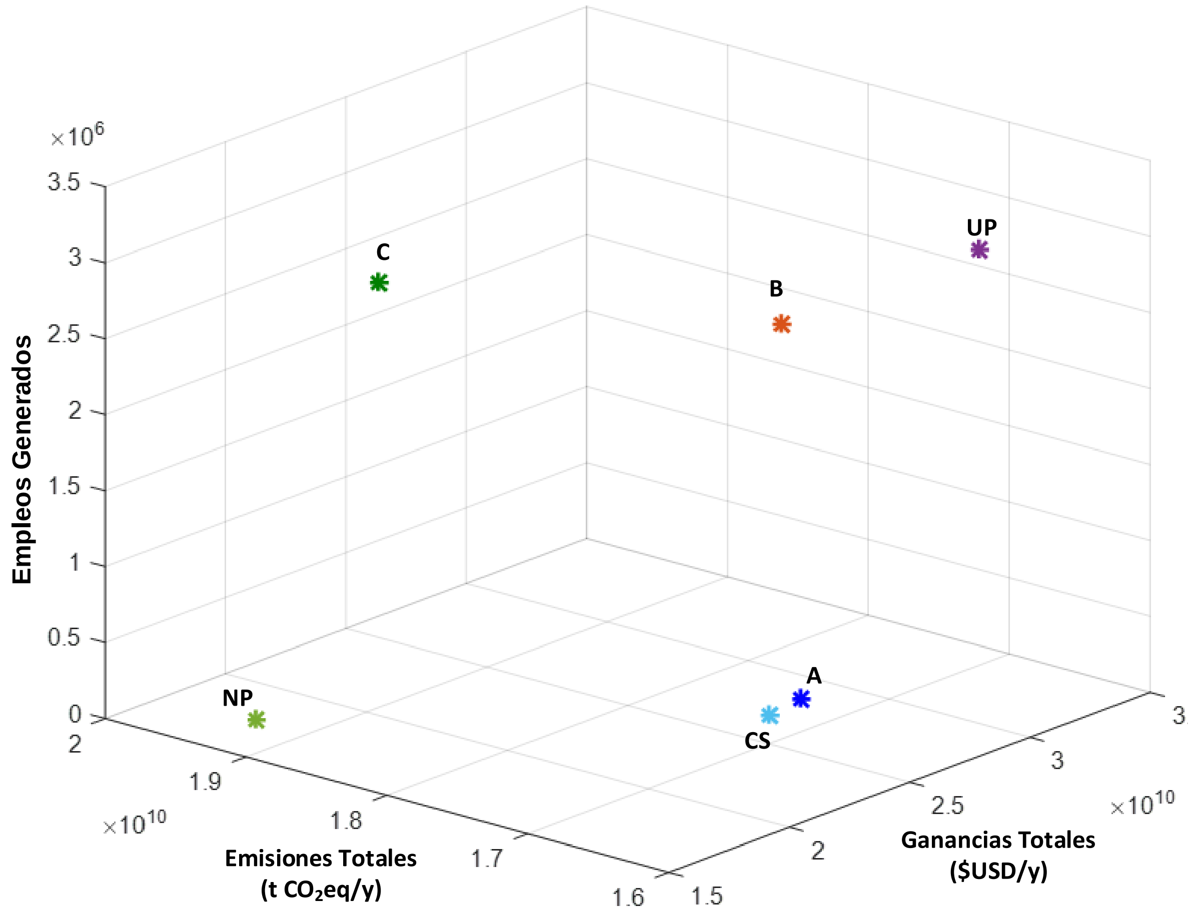

Figura 4.1 Representación gráfica de diversas soluciones para el enfoque propuesto: mejor valor de ganancias (A), mejor valor de empleos (B), mejor valor de emisiones totales (C), solución utópica (UP), solución nadir (NP) y solución compromiso (CS).

La **Tabla 4.3** muestra los resultados numéricos de los puntos detallados en la **Figura 4.1**. Es importante destacar que el punto utópico y la solución compromiso se comparan con las soluciones A, B y C. Por ejemplo, al comparar el punto A con el punto utópico, se puede observar que la ganancia total en el punto A es 7.3% más baja que la ganancia total en el punto utópico, también las emisiones netas son 5.51% más bajas que las emisiones netas en el punto utópico y los empleos totales son 98.77% más bajos que los empleos del punto utópico. Se puede ver que comparando el punto B con respecto al punto utópico para las emisiones, no hay ninguna diferencia. Estos son los mismos en ambos casos, porque en el punto B las emisiones se minimizan y en el punto de utopía las emisiones también se minimizan. Además, no hay diferencia entre el punto C y el UP en relación con el total empleos.

Para comparar los puntos A, B y C con respecto a la solución compromiso (CS), es necesario aclarar que el signo negativo (-) indica la dirección con respecto a CS; por ejemplo, la ganancia total en el punto A es 5.78% mayor que en CS, esto significa que la ganancia en CS está por debajo de la ganancia en A.

Tabla 4.3 Resultados para solución compromiso, punto utópico y soluciones A, B, C; y comparación entre puntos A, B, C con la solución utópica y solución compromiso.

Punto	Tot profit (US MM)	Net emissions (ton x10^8)	Tot jobs
A	28,120	173.20	38,030
B	22,030	164.10	3,085,800
C	17,630	185.10	3,087,000
UP	30,335	164.14	3,086,981
NP	17,197	193.05	32,823
CS	26,581	172.63	29,804
% DIF A-UP	7.30	5.51	98.77
% DIF B-UP	27.37	0	0.04
% DIF C-UP	41.88	12.76	0
%DIF A-CS	-5.79	0.33	-27.59
%DIF B-CS	17.12	-4.94	-10,253.30
%DIF C-CS	33.68	7.22	-10,257.32

La **Figura 4.2** muestra los resultados para diferentes puntos importantes, como la solución compromiso para cada caso ponderado, la solución utópica y nadir (límites inferior y superior), y la solución compromiso global. Es importante enfatizar que la mayoría de los puntos están muy lejos, al menos en un objetivo, del punto utópico.

De esta manera, UP es el punto utópico; esto es, un punto inviable ya que este punto representa los mejores valores posibles para todos los objetivos, lo que no es posible en un sistema real debido a que los objetivos considerados son opuestos. Por lo tanto, se esperan grandes diferencias entre el punto UP y otros puntos tales como A, B, C o CS.

El punto B se obtiene minimizando las emisiones netas; por lo tanto, el punto B representa el punto con el nivel de emisiones más bajo; por ese motivo, se maximiza el número de plantaciones forestales. En este sentido, la cantidad de empleos aumenta ya que las plantaciones forestales tienen el mayor factor unitario de empleos en comparación con las biorefinerías y las refinerías. Además, el punto C representa el número máximo de empleos, lo que corresponde al punto con mayor número de plantaciones forestales.

Es importante recordar que el punto CS no es el punto donde se optimizan los empleos, el beneficio neto y las emisiones. El punto CS corresponde al punto donde se obtienen la mayoría de las soluciones óptimas para cada participante. Cada una de las partes interesadas tiene diferentes prioridades. Por ejemplo, para algunos de ellos, los trabajos no son importantes (consultar **Tabla 4.1**). Además, la **Figura 4.2** permite observar que muchas soluciones de los casos ponderados están cerca de la solución compromiso global, que puede ofrecer una visión general del comportamiento de las soluciones óptimas individuales.

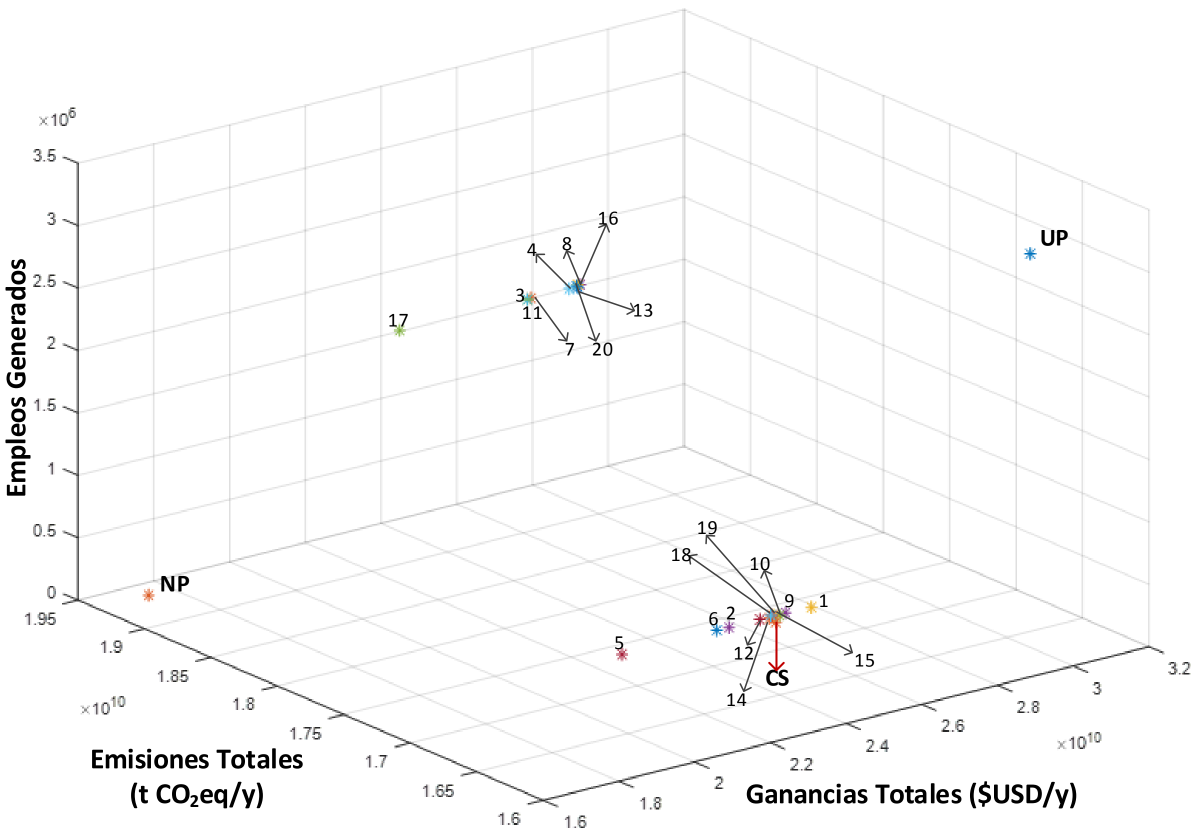

Figura 4.2 Soluciones para el enfoque multi-stakeholder considerando diferentes casos.

Además, la **Figura 4.2** muestra que 11 soluciones óptimas están cerca del punto CS; mientras que sólo una solución está cerca del punto C y las soluciones restantes tienen un nivel de empleos similar al del punto C, pero un valor diferente para ganancias y emisiones.

La **Figura 4.3** muestra las compensaciones y los comportamientos de las funciones objetivo en el conjunto de soluciones compromiso. Primero, debe entenderse que 100 significa que la función está cerca de su valor ideal, mientras que 0 significa que su valor está lejos de esta cantidad, no que el valor de la función sea cien o cero. Por lo tanto, se observa que la solución intenta compensar todos los objetivos, por ejemplo, trata de lograr el máximo beneficio de las refinerías porque el ingreso de estos es mayor que el de biorefinerías y plantaciones forestales. Además, si las biorefinerías son procesos económicamente no viables, la solución intenta reducir las pérdidas de estas, ya que representan un proceso respetuoso con el ambiente y contribuyen a disminución de emisiones. También, en la **Figura 4.3** puede verse que las funciones objetivo de plantaciones forestales están completamente alejadas de su valor ideal; esto es porque su implementación promueve la reducción de las ganancias de las refinerías debido al cargo por carbono emitido.

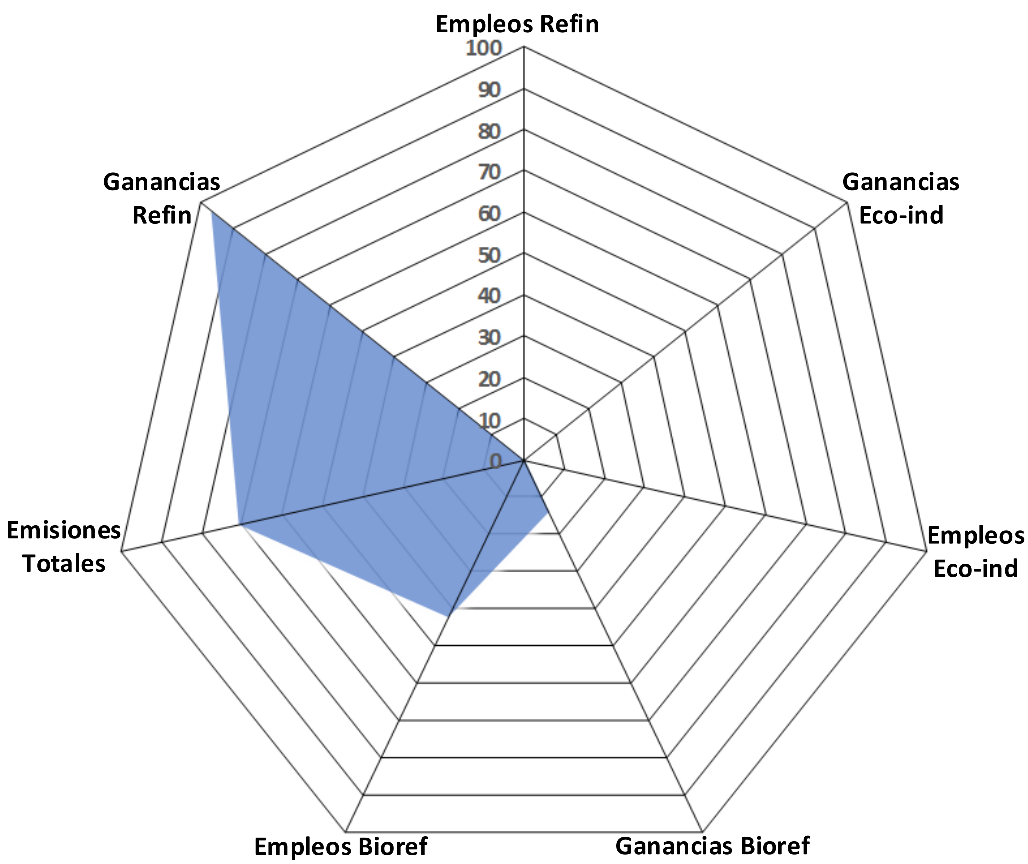

Figura 4.3 Proporción de idealidad satisfecha para cada función objetivo con respecto a la solución compromiso.

Además, se puede observar que la solución compromiso cumple al menos un objetivo económico (es decir, ganancia de refinerías) y objetivos ambientales y sociales (es decir, empleos generados en biorefinerías).

En la **Figura 4.4** es importante señalar que la insatisfacción está relacionada con los pesos de importancia dados para cada caso. Por ejemplo, el caso 14 muestra la mayor proporción de insatisfacción, porque en ese caso los objetivos de plantaciones forestales como ganancias y empleos así como emisiones totales son ponderados; como consecuencia, los objetivos relacionados con eco-industrias no están realmente satisfechos (ver **Figura 4.3**). También, vale la pena señalar que la contribución más importante del uso de esta metodología consiste en lograr una compensación para todos los participantes para que estén satisfechos y proporcionar un marco de discusión para negociar una solución óptima que pueda satisfacer los criterios de la mayoría de los tomadores de decisiones.

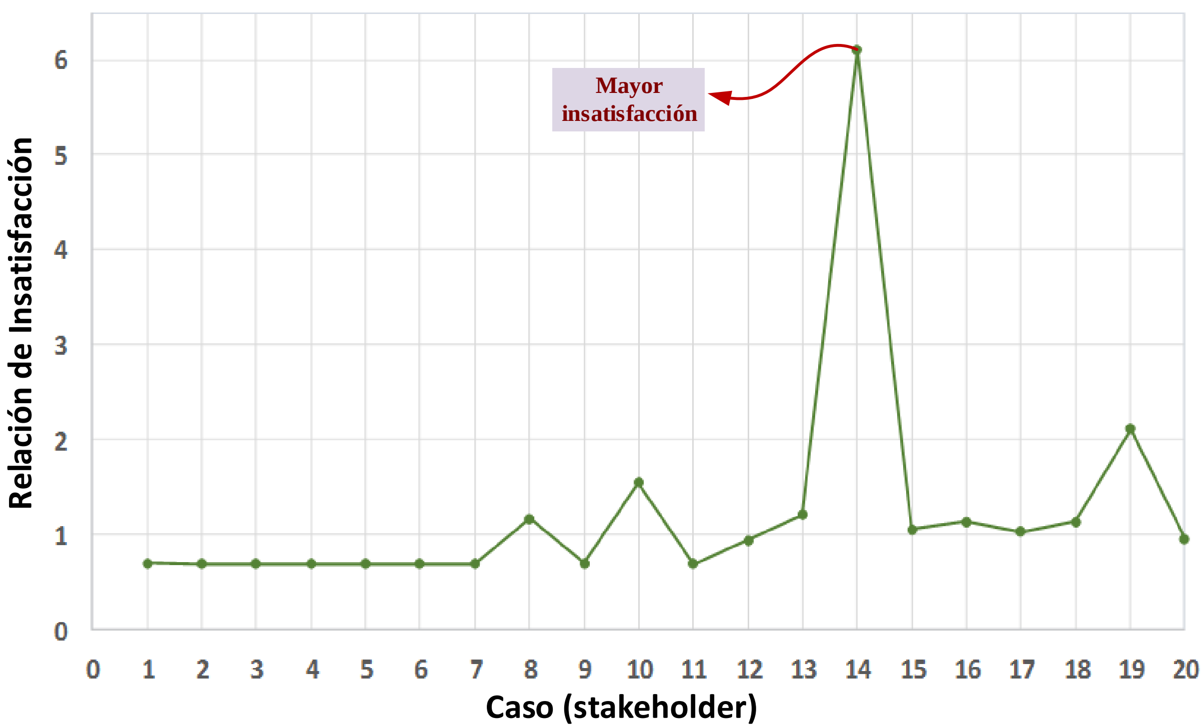

Figura 4.4 Proporción de insatisfacción para cada caso estudiado.

Por un lado, es importante mencionar que el enfoque actual es capaz de generar soluciones óptimas para cada una de las partes interesadas (ver la **Figura 4.2**). Estas soluciones óptimas se obtienen para múltiples partes interesadas asociadas con su propio escenario de prioridad (consultar **Tabla 4.1**); donde, cada escenario denota un participante con diferentes prioridades. Posteriormente, la solución reportada (CS^*) es la solución más cercana al promedio de soluciones óptimas para cada participante. Cabe señalar que algunas partes interesadas pueden estar insatisfechas o en desacuerdo con la solución reportada; sin embargo, la metodología intenta disminuir la insatisfacción.

Por otro lado, la metodología presentada ha considerado que cada parte interesada tiene el mismo peso en el proceso de toma de decisiones, es decir, no se dan preferencias. No obstante, es flexible y las prioridades pueden cambiarse (factor de ponderación diferente en la Ecuación (13)) dependiendo del caso de estudio específico o, si la solución reportada no satisface a la mayoría de los tomadores de decisiones.

CONCLUSIONES

En base a los objetivos se ha desarrollado un modelo de optimización que consideró el uso de una metodología para resolución de problemas múlti-objetivo empleando un enfoque múlti-stakeholder o de múltiples partes interesadas para la toma de decisiones.

Este trabajo presenta una formulación matemática para la planificación e integración del sistema de producción de combustible integrado con plantaciones forestales aplicando el enfoque de solución basado en un esquema múlti-stakeholder o de múltiples partes interesadas. El modelo incorpora los objetivos económicos específicos para las partes interesadas involucradas, así como los empleos creados y las emisiones generales como objetivos individuales. Se presenta un enfoque de optimización de los participantes de múltiples partes interesadas para compensar los objetivos considerados y obtener soluciones factibles cercanas a las mejores soluciones individuales. El enfoque propuesto también permite identificar la insatisfacción de las partes interesadas involucradas en diferentes soluciones factibles. Además, el enfoque propuesto se puede implementar fácilmente para resolver grandes problemas de optimización con múltiples objetivos.

El enfoque propuesto se ha aplicado a un caso de estudio en México. Los resultados mostraron que un cambio en las prioridades de una parte interesada puede producir soluciones insatisfactorias para otros tomadores de decisiones. Además, este enfoque permite proponer una solución con el índice de insatisfacción más bajo teniendo en cuenta diversos objetivos.

Finalmente, es importante señalar que el trabajo ha sido publicado en la revista *ACS Sustainable Chemistry & Engineering* y lleva por nombre *A Multistakeholder Approach for the Optimal Planning of Sustainable Energy Systems*. Además se ha extendido a la incorporación de metodologías basadas en sistemas de información geográfica para tener en cuenta la información sobre los lugares aptos para ubicación de plantaciones forestales y zonas con alto nivel de erosión, y se encuentra en proceso de escritura para publicación.

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APÉNDICE A ARTICULOS PUBLICADOS

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Research Article

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Optimal Design of Energy Systems Involving Pollution Trading through Forest Plantations

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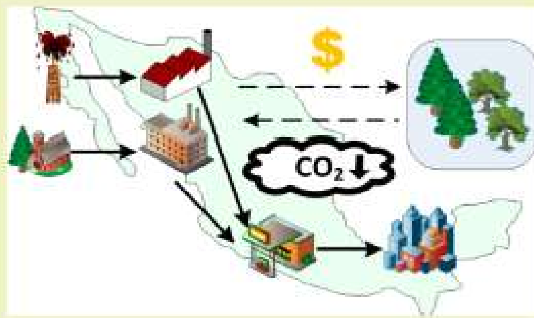
ABSTRACT: The production and use of fossil fuels have caused a drastic increase in greenhouse gas emissions, which is associated directly with the global warming problem. Biofuels and carbon capture through forest plantations are interesting alternatives to address this problem. This paper presents an optimization model for the design of an integrated energy system for producing fuels and biofuels considering the interaction with eco-industries able to capture emissions from biorefineries and refineries and receive a monetary benefit. The proposed mathematical model takes into account the availability of biomass, the production of oil, and a set of existing biorefineries and refineries as well as the possibility to install new eco-industries. The mathematical approach was applied to a nationwide case study for Mexico, considering the creation of new jobs, overall emissions, and net profit as objectives. The results are shown in a Pareto curve, which is useful for making decisions about the interactions between these industries as well as determining the configuration of the supply chain to satisfy the fuel demands.



KEYWORDS: *Biofuel supply chains, Sustainable biorefineries, Optimal planning, Eco-industries, Carbon capture*

INTRODUCTION

Fossil fuels typically generate large amounts of greenhouse gas emissions, which are associated with the global warming problem. It is important to note that small increments in the global temperature involve drastic consequences in the world population. For this reason, Lundgren et al.[1] stated that it is necessary to limit the greenhouse gas emissions from human activities. This way, CO_2 is considered to be a predominant greenhouse gas, which has become an urgent environmental issue (see the work of Sun et al.[2]). Furthermore, several authors have suggested alternatives to address this problem, mainly involving renewable energy sources. In this regard, according to Hong et al.,[3] the use of biofuels is a sustainable way to satisfy the energy needs, because they help to decrease greenhouse gas emissions.[4] Besides, biomass has been identified as a highly potential renewable energy source for producing biofuels, chemicals, and other value-added products using several processing technologies.[5] However, to consider the large scale production of any product, it is crucial to develop tools to aid the decision-making process; for instance, Azapagic and Clift[6] proposed the use of multiobjective optimization to take into account several environmental objective functions. For the case of biofuels from biomass, Torjai et al.[7] stated that the entire supply chain must be analyzed from the economic, environmental, and social points of view. According to Marufuzzaman et al.,[8] biomass is bulky and difficult to transport, impacted by seasonality, and widely dispersed geographically. In addition, Elia and Floudas[9] stated that there is a lack of contributions about the planning of the supply chain from the processing facilities to the final consumers (downriver of the supply chain). Eskandarpour et al.[10] analyzed a set of papers focused on the sustainable supply chain design, and they concluded that there is a lack of works accounting for social objectives. Along this line, Zhang et al.[11] developed an approach for the supply chain design taking into account the total cost, the greenhouse gas emissions, and the lead time as the economic, environmental, and social objectives. Several works have addressed biomass-to-energy supply chains considering different relevant issues.[12] Frombo et al.[13] proposed a decision support system for planning of a system based on energy production from biomass.

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It is possible to note that the supply chain design involves a lot of decisions, which consider complex trade-offs between conflicting objectives,[14] and there is a need of a hierarchical method to balance these contradicting objectives.[15]

Additionally, Azapagic and Clift[16] concluded that the multi-objective optimization considering criteria based on the life cycle assessment is a promising alternative to take decisions in production systems. Also, Kremer et al.[17] discussed the advantages to consider sustainability criteria within the supply chain design. Furthermore, Yue and You[18] stated the challenges associated with the optimal planning of supply chains including selection of feedstocks and harvesting sites, as well as the assortment of products and potential consumers and processing facilities. Consequently, several works have addressed these challenges; for instance, Santibañez-Aguilar et al.[19] presented a mathematical approach to obtain a set of products (ethanol, energy, acetic acid, etc.) from water hyacinth through a distributed biorefining network. Yue et al.[20] applied a life cycle optimization framework to a case study on the hydrocarbon biofuels for a supply chain in Illinois. Martínez-Guido et al.[21] presented a multiobjective optimization approach for the utilization of *Ageratina jocotepecana* to produce ambrox considering the environmental aspect based on the Eco-indicator99 and the economic aspect by the net annual profit. Additionally, Murillo-Alvarado et al.[22] proposed a model for the optimal planning of a supply chain for the use of Agave residues to produce ethanol. Santibañez-Aguilar et al.[23] presented an approach for optimizing a supply chain for the production of biofuels considering environmental, economic and social objectives. More recently, a mixed-integer linear model for the selection of suppliers in a supply chain considering sustainable development and design was developed by Trapp and Sarkis.[24] Garcia and You[25] developed an optimization model for a bioconversion network involving 193 technologies and 129 materials/compounds for producing biofuels. Tong et al.[26] reported an approach for the optimal design of a supply chain to produce biofuels integrated with existing petroleum refineries. Gonela et al.[27] analyzed the interaction between diverse plants to produce ethanol to satisfy high sustainability standards. Furthermore, Fan et al.[28] proposed an optimization approach for supply chain planning considering different transportation ways.

On the other hand, the CO_2 could be considered as a raw material for the production of several useful products. In fact, CO_2 utilization is gaining attention as a greenhouse gas abatement strategy complementary to CO_2 storage (see the work of Schakel et al.[29]). In this context, Schakel et al.[29] explored the production of dimethyl ether from CO_2 through dry reforming of methane. Also, Bonura et al.[30] studied the direct hydrogenation of CO_2 to obtain dimethyl ether via a fixed bed reactor catalyzed with CuZnZr-ferriete hybrids. Besides, Meng et al.[31] proposed a novel material based on zinc glutarate to polymerize CO_2 with propylene to produce poly propylene ether. Moreover, Zhang et al.[32] suggested the production of methanol through reforming and hydrogenation reactions.

Additionally, Tapia and Tan[33] stated that carbon capture and storage is an important way to reduce the industrial emissions. In this context, Park et al.[34] studied the effect of carbon emission cost in the supply chain. It should be noted that CO_2 emissions can be captured through several technologies, which have been addressed in recent papers. For example, Gutiérrez-Arriaga et al.[35] proposed a scheme of mitigation of the CO_2 emissions through a microalgae system in order to produce biodiesel. Notice that the produced biodiesel is fed to a power plant to generate electricity. Similarly, Martín and Grossmann[36] proposed a system to produce methanol and biodiesel with CO_2 capturing. More recently, Bhattacharyya and Shah[37] stated that the amino acid ionic liquids are one of the most interesting and effective way to capture CO_2 because of their low toxicity, biodegradability, and fast reactivity. This way, Darunte et al.[38] evaluated materials based on metal organic frameworks functionalized with amine species to capture CO_2. Moreover, a type of novel adsorbents to capture CO_2 emissions based on nitrogen-doped porous carbon was developed by Chen et al.[39] Wang et al.[40] used a process based on a novel bipolar membrane electrodialysis to treat aniline wastewater and simultaneously capture CO_2.

All of the aforementioned alternatives as well as the forest plantations are attractive to use the CO_2 emissions.[41] Additionally, the scheme of economic incentives for the reduction of greenhouse gas emissions has gained interest in recent years.[42] Verma and Kumar[43] indicated that the scheme of pollution trading and the production of renewable energy can be useful to reduce the greenhouse gas emissions and solve part of the climate change problem. In addition, Lopez-Villarreal et al.[44] showed, via a case study, that pollution trading is a form to satisfy the environmental quality standards as well as cost reductions related to pollutant treatment and reduce the average pollutant emissions per facility in a system. It is worth noting that previous works presented several alternatives for the reduction of the overall environmental impact during the energy production; however, previous approaches did not consider a scheme to integrate two or more ways to reduce the global emissions in the supply chain. On the other hand, Nørstebø et al.[45] stated that the taxation of CO_2 emissions and carbon capture are two ways for reducing the emissions; they analyzed these two measures through a case study of a small industrial park in Norway. However, it should be noticed that none of the previously reported approaches have considered the implementation of a system that considers the interaction between refineries, biorefineries and forest plantations (called eco-industries) through a pollution trading approach to satisfy the fuel demands as well as to help to decrease the associated emissions. Therefore, this paper presents a mathematical programming model for the optimal design of the topology of a supply chain for the production of fuels through refineries and biorefineries integrated with forest plantations focused on decreasing the total greenhouse gas emissions, maximizing the net profit of the system and maximizing the generation of jobs simultaneously. Thus, the proposed approach takes into account two ways for the reduction of greenhouse gas emissions, which is given by the production of biofuels in the biorefineries and the forest plantations to capture CO_2.

PROBLEM STATEMENT

The supply chain of the addressed problem for fuel production through refineries and biorefineries integrated with forest plantations considers several important issues, such as the location of facilities, availability of raw materials, demand of products, inventory of the greenhouse gas emission, as well as the generated jobs for the different activities involved in the supply chain. The addressed problem is based on the schematic representation presented in Figure 1. There is a set of possible oil reservoirs O distributed for the extraction of oil to be sent to refineries I. Also, the supply chain includes a set of possible harvesting sites M to produce different raw materials to be sent to biorefineries B. In addition, there is the possibility to produce

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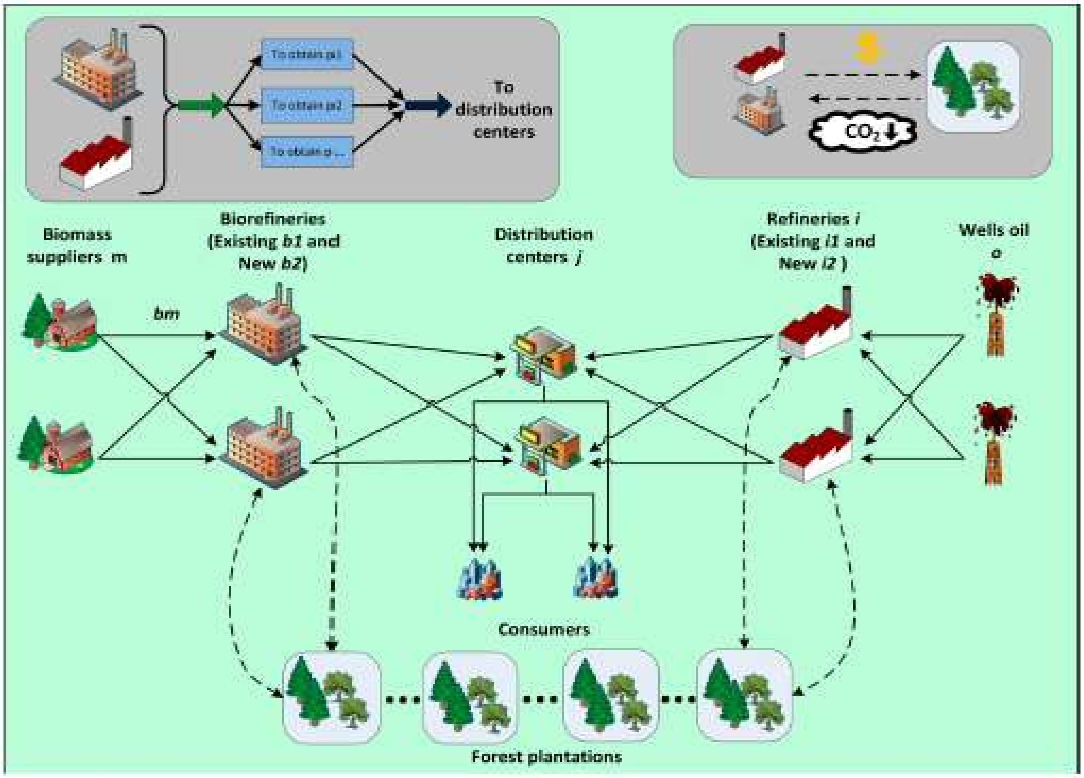

Figure 1. Proposed superstructure for addressing the problem.

fuels from oil in the existing refineries *P*1, as well as installing new refineries to satisfy the fuel demand. On the other hand, it considers the possibility to install new biorefineries to produce biofuels *P*2 and the option to use existing biorefineries. Furthermore, the proposed model incorporates pollution trading concepts to reduce emissions through a set of forest plantations with different capacities and sizes, developed by communities of people dedicated to this activity with an economic retribution. The forest plantations are able to capture part of CO_2 emissions from pollutant industries as refineries and biorefineries. It should be noted that the fuel demand, which can be satisfied via fossil fuels or biofuels, is covered from several distribution centers. Therefore, the problem consists of determining the topology of the supply chain, the flow rates of products and raw materials, capacities of refineries, biorefineries and forest plantations in order to obtain the best environmental, social and economic benefits.

MODEL FORMULATION

This paper proposes an optimization model formulation based on the superstructure presented in Figure 1; the model includes equations for the refineries, biorefineries, and forest plantations as follows.

$$F_i^{\mathrm{oil}} = \sum_o f_{o,i}^{\mathrm{oil1}}, \quad \forall\, i \tag{1}$$

Equations for Refineries. *Mass Balance for Refineries.* Equation 1 represents that the total flow of oil inlet to the refineries (F_i^{oil}), given in tons per day, is equal to the sum of the flow of oil that is obtained from different wells ($\sum_o f_{o,i}^{\mathrm{oil1}}$).

$$F_{p1,i}^{\mathrm{product\text{-}ref}} = \alpha_{p1,i}^{\mathrm{product\text{-}ref}} \cdot F_i^{\mathrm{oil}}, \quad \forall\, i, \forall\, p1 \tag{2}$$

Refinery Production. Equation 2 is used to calculate the refinery production; this equation states that the total flow of products from refineries ($F_{p1,i}^{\mathrm{product\text{-}ref}}$) are equal to a conversion factor to obtain the refinery production ($\alpha_{p1,i}^{\mathrm{product\text{-}ref}}$) multiplied by the total oil in the refineries (F_i^{oil}).

$$F_{p1,i}^{\mathrm{product\text{-}ref}} = \sum_j f_{p1,i,j}^{\mathrm{product\text{-}ref1}}, \quad \forall\, i, \forall\, p1 \tag{3}$$

Distribution of Products from Refineries. Equation 3 states that the product in the refineries ($F_{p1,i}^{\mathrm{product\text{-}ref}}$) can be distributed to any distribution center ($\sum_j f_{p1,i,j}^{\mathrm{product\text{-}ref1}}$).

Constraints for Existing Refineries. Maximum capacity

$$F_{i1}^{\mathrm{oil}} \le F_{i1}^{\mathrm{oilMAX1}}, \quad \forall\, i1 \tag{4}$$

Equation 4 represents a constraint for the maximum capacity given for existing refineries; the total flow of oil in the existing refineries (F_{i1}^{oil}) must be lower than the maximum capacity of processing for the existing refineries ($F_{i1}^{\mathrm{oilMAX1}}$).

Constraints for New Refineries. For modeling the new refineries, the existence and capacity is stated through the following disjunction:

$$\vee \begin{bmatrix} Y_{i2}^{\mathrm{ref}} \\ F_{i2}^{\mathrm{oilMIN}} \le F_{i2}^{\mathrm{oil}} \le F_{i2}^{\mathrm{oilMAX2}} \\ C_{i2}^{\mathrm{Capref}} = K_F \cdot (F_{i2}^{\mathrm{Costref}} + V_{i2}^{\mathrm{Costref}} (F_{i2}^{\mathrm{oil}})^{\gamma_{i2}^{\mathrm{ref}}}) \end{bmatrix}, \quad \forall\, i2$$

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which is reformulated algebraically as follows

$$F_{i2}^{oilMIN} \cdot y_{i2}^{ref} \leq F_{i2}^{oil} \leq F_{i2}^{oilMAX2} \cdot y_{i2}^{ref}, \quad \forall\, i2 \tag{5}$$

$$C_{i2}^{Capref} = K_F \cdot (F_{i2}^{Costref} \cdot y_{i2}^{ref} + V_{i2}^{Costref} (F_{i2}^{oil})^{y_{i2}^{ref}}), \quad \forall\, i2 \tag{6}$$

Previous equations are the reformulation of the disjunction for the existence of new refineries. Equation 5 states that total flow of oil in new refineries (F_{i2}^{oil}) is greater than the minimum capacity of processing for new refineries (F_{i2}^{oilMIN}) multiplied by a binary variable for the existence of new refineries (y_{i2}^{ref}) and lower than the maximum capacity of processing for new refineries($F_{i2}^{oilMAX2}$) multiplied by the same binary variable for the existence of new refineries (y_{i2}^{ref}). Additionally, eq 6 represents the capital cost of new refineries when they exist, which accounts for the fixed cost ($F_{i2}^{Costref}$), the variable cost ($V_{i2}^{Costref}$), and the factor used to annualize the investment (K_F). It should be noted that there is not any problem when the variable (F_{i2}^{oil}) is zero (in eq 6), because in this case the binary variable (y_{i2}^{ref}) is zero (from relationship 5), and this way the associated cost (C_{i2}^{Capref}) is zero.

Refinery Operating Cost. The operating cost of refineries (C_i^{opref}) is determined by the unitary operating cost (OC_i^{ref}) multiplied by the total petroleum flow in the refineries (F_i^{oil}), where the operational duration (H_Y) is 365 days in each period.

$$C_i^{opref} = H_Y \cdot OC_i^{ref} \cdot F_i^{oil}, \quad \forall\, i \tag{7}$$

Cost of Oil for Refineries. The cost of petroleum for refineries ($Cost_i^{oil}$) involves the sum of the unitary cost of oil ($UC_{o,i}^{oil}$) multiplied by the flow of oil that is extracted from the well ($f_{o,i}^{oil1}$) and the operating days (H_Y), which is represented as follows:

$$Cost_i^{oil} = \sum_o UC_{o,i}^{oil} \cdot (H_Y \cdot f_{o,i}^{oil1}), \quad \forall\, i \tag{8}$$

Revenue for Selling Products of Refineries. The revenue of refineries ($Revenue_i^{sold\text{-}product\text{-}ref}$) accounts for the selling of products and is determined by the sum of the unitary selling cost for the products ($UC_{p1,i}^{selling\text{-}product\text{-}ref}$) multiplied by the total flow of products from refineries ($F_{p1,i}^{product\text{-}ref}$) and the operating days (H_Y):

$$Revenue_i^{sold\text{-}product\text{-}ref} = \sum_{p1} UC_{p1,i}^{selling\text{-}product\text{-}ref} \cdot (H_Y \cdot F_{p1,i}^{product\text{-}ref}), \quad \forall\, i \tag{9}$$

Total Profit Per Refinery. The total profit for refineries ($Profit^{refinery}$) includes the revenue by the product sale of refineries ($Revenue_i^{sold\text{-}product\text{-}ref}$) and all the involved costs, including the cost of crude oil ($Cost_i^{oil}$), operating cost of refineries (C_i^{opref}), capital cost of new refineries (C_{i2}^{Capref}), and transportation cost of oil from wells to existing and new refineries ($C_{i1}^{trans\text{-}oil\text{-}exis}$, $C_{i2}^{trans\text{-}oil\text{-}new}$), and transportation cost of refined products from existing and new refineries to distribution centers ($C_{i1}^{trans\text{-}products\text{-}ref\text{-}exis}$, $C_{i2}^{trans\text{-}products\text{-}ref\text{-}new}$). Also, the refineries' total profit considers a cost by emissions; it means that refineries should pay to eco-industries to reduce their emissions. The cost by emissions accounts for the unitary cost of emissions ($CEmis_i^{ref}$) multiplied by the amount of captured emissions from refineries by eco-industries ($Emcap_i^{refinery}$):

$$\begin{aligned} Profit^{refinery} = & \sum_i Revenue_i^{sold\text{-}product\text{-}ref} - \sum_i Cost_i^{oil} \\ & - \sum_i C_i^{opref} - \sum_{i2} C_{i2}^{Capref} - \sum_{i1} C_{i1}^{trans\text{-}oil\text{-}exis} \\ & - \sum_{i1} C_{i1}^{trans\text{-}products\text{-}ref\text{-}exis} - \sum_{i2} C_{i2}^{trans\text{-}oil\text{-}new} \\ & - \sum_{i2} C_{i2}^{trans\text{-}products\text{-}ref\text{-}new} - \sum_i CEmis_i^{ref} \cdot Emcap_i^{refinery} \end{aligned} \tag{10}$$

In this way, a constraint for the amount of captured emissions from refineries by eco-industries is needed because these emissions do not have to be greater than the total emissions per refinery:

$$Emcap_i^{refinery} \leq Em_i^{refinery}, \quad \forall\, i \tag{11}$$

Equations for Biorefineries. *Biomass Balance in Biorefineries.* The biomass balance in biorefineries ($F_{bm,b}^{biomass}$), given in tons per day, is equal to the sum of the amount of biomass that arrives from the biomass fields ($\sum_m f_{bm,m,b}^{biomass1}$):

$$F_{bm,b}^{biomass} = \sum_m f_{bm,m,b}^{biomass1}, \quad \forall b,\, bm \tag{12}$$

Biomass Balance in Fields. The total amount of biomass distributed from fields to biorefineries ($F_{bm,m}^{biomass\text{-}field}$) is determined by the sum of the amount of biomass that is distributed from each biomass field to biorefineries ($\sum_b f_{bm,m,b}^{biomass1}$) as follows:

$$F_{bm,m}^{biomass\text{-}field} = \sum_b f_{bm,m,b}^{biomass1}, \quad \forall bm,\, m \tag{13}$$

Availability Constraint for Biomass in Fields. The biomass in field is limited by the maximum amount of biomass available in each field as follows:

$$F_{bm,m}^{biomass\text{-}field} \leq \max F_{bm,m}^{biomass\text{-}field}, \quad \forall\, bm,\, m \tag{14}$$

Biorefinery Production. The production of biorefineries states that the total flow of bioproducts from biorefineries ($F_{p2,b}^{product\text{-}bioref}$) is equal to the sum of a conversion factor ($\alpha_{p2,bm,b}^{product\text{-}bioref}$) multiplied by the total flow of biomass in biorefineries ($F_{bm,b}^{biomass}$):

$$F_{p2,b}^{product\text{-}Bioref} = \sum_{bm} \alpha_{p2,bm,b}^{product\text{-}bioref} \cdot F_{bm,b}^{biomass}, \quad \forall\, p2,\, b \tag{15}$$

Distribution of Products from Biorefineries. The products should be distributed to different distribution centers. The total amount of product from biorefineries ($F_{p2,b}^{product\text{-}bioref}$) is equal to the sum of bioproducts shipped to the distribution centers ($f_{p2,b,j}^{product\text{-}bioref}$):

$$F_{p2,b}^{product\text{-}bioref} = \sum_j f_{p2,b,j}^{product\text{-}bioref1}, \quad \forall\, p2,\, b \tag{16}$$

Constraints for Existing Biorefineries. The processed raw material in any existing biorefinery ($F_{bm,b1}^{biomass}$) must be lower than the maximum installed processing capacity ($F_{b1}^{biomass\text{-}MAX1}$):

$$\sum_{bm} F_{bm,b1}^{biomass} \leq F_{b1}^{biomass\text{-}MAX1}, \quad \forall\, b1 \tag{17}$$

Constraints for New Biorefineries. For modeling the addition of a new biorefinery, the following disjunction is proposed:

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$$\underset{b2}{\vee}\left[\begin{array}{c} Y_{b2}^{\text{bioref}} \\ F_{b2}^{\text{biomassMIN}} \le \sum_{bm} F_{bm,b2}^{\text{biomass}} \le F_{b2}^{\text{biomassMAX2}} \\ C_{b2}^{\text{Capbioref}} = F_{b2}^{\text{Costbioref}} + \sum_{bm} (V_{bm,b2}^{\text{Costbioref}} \cdot (F_{bm,b2}^{\text{biomass}})^{\gamma_{b2}^{\text{bioref}}}) \end{array}\right]$$

Previous disjunction states that when the new biorefinery is needed (the Boolean variable Y_{b2}^{bioref} is true), the biorefinery in site $b2$ exists and then the capacity and associated cost are determined. It is worth noting that previous disjunction has to be reformulated as algebraic equations to include it in the mathematical model. In this regard, the processed raw material in the new biorefinery $b2$ ($F_{bm,b2}^{\text{biomass}}$) should be greater than the minimum capacity ($F_{b2}^{\text{biomassMIN}}$) and lower than the maximum allowed capacity ($F_{b2}^{\text{biomassMAX2}}$). This is modeled through the binary variable y_{b2}^{bioref} that is 1 when the Boolean variable Y_{b2}^{bioref} is true; otherwise, it is zero

$$F_{b2}^{\text{biomassMIN}} \cdot y_{b2}^{\text{bioref}} \le \sum_{bm} F_{bm,b2}^{\text{biomass}} \le F_{b2}^{\text{biomassMAX2}} \cdot y_{b2}^{\text{bioref}}, \quad \forall\ b2 \tag{18}$$

Furthermore, an equation is needed for the capital cost of new biorefineries, which includes a fixed cost ($F_{b2}^{\text{Costbioref}}$) multiplied by the binary variable to define the existence of the new biorefinery (y_{b2}^{bioref}) plus a unitary variable cost ($V_{bm,b2}^{\text{Costbioref}}$) multiplied by the amount of raw material that is processed in the biorefinery ($F_{bm,b2}^{\text{biomass}}$) accounting for the exponent ($\gamma_{b2}^{\text{bioref}}$) to consider the economies of scale. It is important to note that the capital is annualized by the factor K_F.

$$C_{b2}^{\text{Capbioref}} = K_F \cdot (F_{b2}^{\text{Costbioref}} \cdot y_{b2}^{\text{bioref}} + \sum_{bm} (V_{bm,b2}^{\text{Costbioref}} \cdot (F_{bm,b2}^{\text{biomass}})^{\gamma_{b2}^{\text{bioref}}})), \quad \forall\ b2 \tag{19}$$

Biorefinery Operating Cost. The operating cost for biorefineries (C_b^{opbioref}) is given by the sum of the flows of processed biomass ($F_{bm,b}^{\text{biomass}}$) multiplied by the unitary operating cost ($OC_{bm,b}^{\text{bioref}}$) considering the operating days (H_Y):

$$C_b^{\text{opbioref}} = H_Y \cdot \sum_{bm} OC_{bm,b}^{\text{bioref}} \cdot F_{bm,b}^{\text{biomass}}, \quad \forall\ b \tag{20}$$

Biomass Production Cost for Biorefineries. The model takes into account the cost for the biomass production in each field ($\text{Cost}_b^{\text{biomass-growth}}$). This cost is added to the biorefineries because biomass is the main raw material to this type of processing plants. Thus, the cost for the biomass production ($\text{Cost}_b^{\text{biomass-growth}}$) is equal to the sum of a unitary cost for the biomass production ($UC_{bm,b,m}^{\text{biomass-growth}}$) multiplied by the total flow of biomass ($F_{bm,b}^{\text{biomass}}$):

$$\text{Cost}_b^{\text{biomass-growth}} = \sum_{bm} \sum_{m} UC_{bm,b,m}^{\text{biomass-growth}} \cdot (H_Y \cdot F_{bm,b}^{\text{biomass}}), \quad \forall\ b \tag{21}$$

Revenue for Selling of Products in Biorefineries. The model incorporates the economic income for selling biorefinery products. The revenue for selling of bioproducts ($\text{Revenue}_b^{\text{sold-prod-bioref}}$) is equal to the sum of a unitary product cost ($UC_{p2,b}^{\text{revenue-prod-bioref}}$) multiplied by the flow of product sold, which is the total flow of product produced in any biorefinery ($F_{p2,b}^{\text{product-bioref}}$). It should be noted that the days of operation should be taken into account to get an annual basis:

$$\text{Revenue}_b^{\text{sold-prod-bioref}} = \sum_{p2} UC_{p2,b}^{\text{revenue-prod-bioref}} \cdot (H_Y \cdot F_{p2,b}^{\text{product-bioref}}), \quad \forall\ b \tag{22}$$

Total Profit per Biorefinery. The net profit per biorefinery ($\text{Profit}^{\text{bioref}}$) is equal to the sum of the total revenue for selling of products ($\text{Revenue}_b^{\text{sold-prod-bioref}}$), minus the sum of the biomass cultivation cost ($\text{Cost}_b^{\text{biomass-growth}}$), operating ($C_b^{\text{opbioref}}$), and capital ($C_{b2}^{\text{Capbioref}}$) costs for the processing plants, transportation of raw materials ($C_{b1}^{\text{trans-biomass-exis}}$, $C_{b2}^{\text{trans-biomass-new}}$), and product ($C_{b1}^{\text{trans-product-bioref-exis}}$, $C_{b2}^{\text{trans-product-bioref-new}}$), and the cost for their emissions ($\text{CEmis}_b^{\text{bioref}} \cdot \text{Emcap}_b^{\text{biorefinery}}$), which is defined in a similar way that the cost for emissions by refineries:

$$\begin{aligned} \text{Profit}^{\text{bioref}} = & \sum_b \text{Revenue}_b^{\text{sold-prod-bioref}} \\ & - \sum_b \text{Cost}_b^{\text{biomass-growth}} - \sum_{b2} C_{b2}^{\text{Capbioref}} - \sum_b C_b^{\text{opbioref}} \\ & - \sum_{b1} C_{b1}^{\text{trans-biomass-exis}} - \sum_{b1} C_{b1}^{\text{trans-product-bioref-exis}} \\ & - \sum_{b2} C_{b2}^{\text{trans-biomass-new}} - \sum_{b2} C_{b2}^{\text{trans-product-bioref-new}} \\ & - \sum_b \text{CEmis}_b^{\text{bioref}} \cdot \text{Emcap}_b^{\text{biorefinery}} \end{aligned} \tag{23}$$

Also a constraint is needed to limit the amount of captured emissions from biorefineries through eco-industries ($\text{Emcap}_b^{\text{biorefinery}}$), because the captured emissions should be lower than the total emissions of biorefineries ($\text{Em}_b^{\text{bioref}}$):

$$\text{Emcap}_b^{\text{biorefinery}} \le \text{Em}_b^{\text{bioref}}, \quad \forall\ b \tag{24}$$

Equations for Forest Plantations. *Operating Cost for Forest Plantations.* The operating cost for forest plantations (C_e^{opecoind}) is equal to the unitary operating cost (OC_e^{opecoind}) multiplied by the total number of trees of each eco-industry (N_{Te}):

$$C_e^{\text{opecoind}} = OC_e^{\text{opecoind}} \cdot N_{Te}, \quad \forall\ e \tag{25}$$

Limits for Forest Plantations. The capacity of forest plantations is limited by the available land for forest plantations; therefore, upper and lower limits are needed for the used land in the implemented eco-industries. The total amount of trees for each eco-industry (N_{Te}) multiplied by the area of land that is needed for each tree (Uland_e) represents the area of land required for each eco-industry. This area must be lower than the upper limit of available land ($\text{Dland}_e^{\text{Max}}$) multiplied by a binary variable for the existence of eco-industries (y_e^{ecoind}), also the occupied land should be greater than the lower limit of available land ($\text{Dland}_e^{\text{Min}}$) multiplied by the same binary variable for the existence of eco-industries (y_e^{ecoind}):

$$\text{Dland}_e^{\text{Max}} \cdot y_e^{\text{ecoind}} \ge N_{Te} \cdot \text{Uland}_e \ge \text{Dland}_e^{\text{Min}} \cdot y_e^{\text{ecoind}}, \quad \forall\ e \tag{26}$$

Capital Cost for Eco-industries. The capital cost of eco-industries is defined by a fixed cost (F_e^{Costeco}) multiplied by a binary variable for the existence of eco-industries in a given location, plus a variable cost (V_e^{Costeco}) multiplied by the total number of trees for each eco-industry and an exponent of capacity $(N_{Te})^{\gamma_e^{\text{ecoind}}}$ accounting for the factor used to annualize the inversion (K_F):

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$$C_e^{\text{Capecoind}} = K_F \cdot (F_e^{\text{Costeco}} \cdot y_e^{\text{ecoind}} + V_e^{\text{Costeco}} (N_{Te})^{\gamma_e^{\text{ecoind}}}), \quad \forall\ e \qquad (27)$$

Total Cost of Eco-industries. The sum of the operating and capital costs of eco-industries represents the total cost of eco-industries:

$$C_e^{\text{Totalecoind}} = C_e^{\text{opecoind}} + C_e^{\text{Caepcoind}}, \quad \forall\ e \qquad (28)$$

Profit of Eco-industries. The profit for eco-industries depends on the income by the captured emissions from refineries and biorefineries as well as the associated cost for the installation and operating cost of eco-industries; thus, the equation involves the cost of emissions of refineries ($\text{CEmis}_i^{\text{ref}}$) and biorefineries ($\text{CEmis}_b^{\text{bioref}}$) and the amount of these emissions captured for the eco-industries ($\text{Emcap}_b^{\text{biorefinery}}$), minus the total cost of eco-industries ($C_e^{\text{Totalecoind}}$):

$$\text{Profit}^{\text{ecoind}} = \sum_i \text{CEmis}_i^{\text{ref}} \cdot \text{Emcap}_i^{\text{Refinery}} + \sum_b \text{CEmis}_b^{\text{bioref}} \cdot \text{Emcap}_b^{\text{biorefinery}} - \sum_e C_e^{\text{Totalecoind}} \qquad (29)$$

It should be noticed that the concept of carbon tax is included in the paper; the value of the carbon tax affects directly the configuration of the supply chain because this value is related with the revenues of the forest plantations. In this context, if the value of carbon tax is high, then the number of forest plantations increases. It is important to mention that the value of carbon tax for the refineries is higher than the value for biorefineries; which promotes the installation of biorefineries instead of refineries to maximize the captured emissions by the forest plantations.

Equations for Transportation Costs for Different Materials. In this section, the relationships for the costs associated with transport different materials through the supply chain are presented.

Oil from Well Oil to Existing Refineries. The transportation cost of oil from the oil well to existing refineries ($C_{i1}^{\text{trans-oil-exis}}$) is equal to a unitary cost for the transportation of oil ($\text{UC}_{o,i1}^{\text{pumping-oil-exis}}$) multiplied by the oil flow distributed from the wells to the existing refineries ($f_{o,i1}^{\text{oil1}}$). It is important to note that there are several types of transportation for oil as truck, duct or vessel; and these types are defined previously according to the location of the existing refineries and wells:

$$C_{i1}^{\text{trans-oil-exis}} = \sum_o \text{UC}_{o,i1}^{\text{pumping-oil-exis}} \cdot (H_Y \cdot f_{o,i1}^{\text{oil1}}), \quad \forall\ i1 \qquad (30)$$

Products from Existing Refineries to Distribution Centers. The transportation cost for the distributed products from refineries to distribution centers ($C_{i1}^{\text{trans-products-ref-exis}}$) is equal to the sum of a unitary transportation cost for products ($\text{UC}_{p1,i1,j}^{\text{trans-product-ref}}$) multiplied by the total flow rate of transported product from refineries to distribution centers ($f_{p1,i1,j}^{\text{product-ref1}}$), as well as the days of operation (H_Y), to obtain the annual amount of product that is transported:

$$C_{i1}^{\text{trans-products-ref-exis}} = \sum_{p1} \sum_j \text{UC}_{p1,i1,j}^{\text{trans-product-ref}} \cdot (H_Y \cdot f_{p1,i1,j}^{\text{product-ref1}}), \quad \forall\ i1 \qquad (31)$$

Oil from Wells to New Refineries. The distribution of the oil from the wells to the new refineries is taken into account. It should be noticed that there are some differences between the transportation to the existing and new refineries, since the transportation to the new refineries needs the installation of infrastructure. Therefore, the capital cost for transportation of oil from the oil well to the new refineries ($C_{i2}^{\text{Captrans-oil}}$) is equal to the sum of a fixed cost ($F_{o,i2}^{\text{cost-pip-oil}}$) multiplied by the binary variable for the existence of the transportation infrastructure ($y_{o,i2}^{\text{pip-oil-ref}}$) plus a variable cost ($V_{o,i2}^{\text{cost-oil}}$) multiplied by the total flow of transported oil ($f_{o,i2}^{\text{oil1}}$) elevated to the exponent ($\gamma_{i2}^{\text{trans-ref1}}$) considering the annualization factor (K_F):

$$C_{i2}^{\text{Captrans-oil}} = \sum_o K_F \cdot (F_{o,i2}^{\text{cost-pip-oil}} \cdot y_{o,i2}^{\text{pip-oil-ref}} + V_{o,i2}^{\text{cost-oil}} \cdot (f_{o,i2}^{\text{oil1}})^{\gamma_{i2}^{\text{trans-ref1}}}), \quad \forall\ i2 \qquad (32)$$

The model takes into account another transportation cost for oil, which depends exclusively on the flow of oil transported. This transportation cost ($C_{i2}^{\text{optrans-oil}}$) is equal to a unitary cost ($\text{UC}_{o,i2}^{\text{pumping-oil-new}}$) multiplied by the operating days (H_Y) and the flow of oil from the well to new refineries ($f_{o,i1}^{\text{oil1}}$):

$$C_{i2}^{\text{optrans-oil}} = \sum_o \text{UC}_{o,i2}^{\text{pumping-oil-new}} \cdot (H_Y \cdot f_{o,i2}^{\text{oil1}}), \quad \forall\ i2 \qquad (33)$$

Once that both of previous transportation costs are defined, it is possible to obtain the total transportation cost for oil from wells to new refineries ($C_{i2}^{\text{trans-oil-new}}$), which is equal to the sum of the capital cost for the transportation infrastructure ($C_{i2}^{\text{Captrans-oil}}$) plus the transportation cost for the amount of oil to the new refineries ($C_{i2}^{\text{optrans-oil}}$):

$$C_{i2}^{\text{trans-oil-new}} = C_{i2}^{\text{Captrans-oil}} + C_{i2}^{\text{optrans-oil}}, \quad \forall\ i2 \qquad (34)$$

The flow of oil that is transported from the oil well to the new refineries is limited between lower and upper limits, because the construction of new infrastructure to transport the oil could not be economically attractive if the amount of transported oil is lower than a minimum limit or greater than the maximum limit. Therefore, the transported flow rate of oil ($f_{o,i2}^{\text{oil1}}$) must be lower than an upper limit for the transportation to the new refineries ($\text{fl}_{o,i2}^{\text{oil-MAX}}$) multiplied by the binary variable to define if the transportation activity is active ($y_{o,i2}^{\text{pip-oil-ref}}$). Also, the transported flow rate of oil ($f_{o,i2}^{\text{oil1}}$) must be greater than a lower limit for the transportation to the new refineries ($\text{fl}_{o,i2}^{\text{oil-MIN}}$) multiplied by the binary variable to decide if the transportation of oil is active ($y_{o,i2}^{\text{pip-oil-ref}}$):

$$\text{fl}_{o,i2}^{\text{oil-MIN}} \cdot y_{o,i2}^{\text{pip-oil-ref}} \leq f_{o,i2}^{\text{oil1}} \leq \text{fl}_{o,i2}^{\text{oil-MAX}} \cdot y_{o,i2}^{\text{pip-oil-ref}}, \quad \forall\ o, \forall\ i2 \qquad (35)$$

Products from New Refineries to Distribution Centers. The new refineries are able to produce several value-added products from the received oil. These products should be distributed to distribution centers and there is an associated cost to this activity. This transportation cost ($C_{i2}^{\text{optrans-products-ref}}$) is given by the sum of a unitary transportation cost ($\text{UC}_{p1,i2,j}^{\text{trans-prod-ref-new}}$) multiplied by the operating days (H_Y) and the transported

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flow rate ($f_{p1,i2,j}^{\text{product-refl}}$):

$$C_{i2}^{\text{optrans-products-ref}} = \sum_{p1}\sum_{j} \text{UC}_{p1,i2,j}^{\text{trans-prod-ref-new}} \cdot (H_Y \cdot f_{p1,i2,j}^{\text{product-refl}}), \quad \forall\ i2 \tag{36}$$

The mathematical approach also takes into account the capital cost for the installation of the needed infrastructure ($C_{i2}^{\text{Captrans-product-ref}}$). This capital cost is equal to a fixed cost ($F_{p1,i2,j}^{\text{cost-pip-prod-ref}}$) multiplied by the binary variable for transportation ($y_{p1,i2,j}^{\text{pip-prod-ref}}$) plus a variable cost ($V_{p1,i2,j}^{\text{cost-prod-ref}}$) multiplied by the distributed flow rate of products ($f_{p1,i2,j}^{\text{product-refl}}$) elevated to a capacity exponent ($\gamma_{i2}^{\text{trans-ref2}}$):

$$C_{i2}^{\text{Captrans-products-ref}} = \sum_{p1}\sum_{j} K_F \cdot (F_{p1,i2,j}^{\text{cost-pip-prod-ref}} \cdot y_{p1,i2,j}^{\text{pip-product-ref}} + V_{p1,i2,j}^{\text{cost-prod-ref}} \cdot (f_{p1,i2,j}^{\text{product-refl}})^{\gamma_{i2}^{\text{trans-ref2}}}), \quad \forall\ i2 \tag{37}$$

The total transportation cost for products from the new refineries to distribution centers ($C_{i2}^{\text{trans-product-ref-new}}$) is equal to the operational transportation cost ($C_{i2}^{\text{optrans-product-ref}}$) plus the capital transportation cost for new infrastructure ($C_{i2}^{\text{Captrans-product-ref}}$):

$$C_{i2}^{\text{trans-products-ref-new}} = C_{i2}^{\text{Captrans-products-ref}} + C_{i2}^{\text{optrans-products-ref}}, \quad \forall\ i2 \tag{38}$$

The mathematical formulation considers several limits to define if there is transportation activities of products between the new refineries and the distribution centers. Binary variables are included and the transported flow rate ($f_{p1,i2,j}^{\text{product-refl}}$) must be lower than the maximum transportation limit ($f_{p1,i2,j}^{\text{product-ref-MAX}}$) multiplied by the binary variable to determine the transportation activity ($y_{p1,i2,j}^{\text{pip-product-ref}}$), and greater than the minimum limit ($f_{p1,i2,j}^{\text{product-ref-MIN}}$) multiplied by the same binary variable:

$$f_{p1,i2,j}^{\text{product-ref-MIN}} \cdot y_{p1,i2,j}^{\text{pip-product-ref}} \le f_{p1,i2,j}^{\text{product-refl}} \le f_{p1,i2,j}^{\text{product-ref-MAX}} \cdot y_{p1,i2,j}^{\text{pip-product-ref}}, \quad \forall\ p1, \forall\ i2, \forall\ j \tag{39}$$

Biomass from Fields to Existing Biorefineries. The biomass can be transported from the fields to biorefineries. For the case of the existing biorefineries, the transportation cost ($C_{b1}^{\text{trans-biomass-exis}}$) is obtained by the sum of a unitary transportation cost for biomass ($\text{UC}_{bm,m,b1}^{\text{trans-biomass-exist}}$) multiplied by the amount of transported biomass ($f_{bm,m,b1}^{\text{biomass1}}$) as well as the operating days (H_Y):

$$C_{b1}^{\text{trans-biomass-exis}} = \sum_{m}\sum_{bm} \text{UC}_{bm,m,b1}^{\text{trans-biomass-exist}} \cdot (H_Y \cdot f_{bm,m,b1}^{\text{biomass1}}), \quad \forall\ b1 \tag{40}$$

Products from Existing Biorefineries to Distribution Centers. The bioproducts are distributed from the biorefineries to distribution centers, and the associated transportation cost ($C_{b1}^{\text{trans-product-bioref-exis}}$) is equal to the sum of a unitary transportation cost for bioproducts ($\text{UC}_{p2,b1,j}^{\text{trans-prod-bior-exis}}$) multiplied by the amount of transported bioproducts ($f_{p2,b1,j}^{\text{product-biorefl}}$) and the operating days (H_Y):

$$C_{b1}^{\text{trans-product-bioref-exis}} = \sum_{p2}\sum_{j} \text{UC}_{p2,b1,j}^{\text{trans-prod-bior-exis}} \cdot (H_Y \cdot f_{p2,b1,j}^{\text{product-biorefl}}), \quad \forall\ b1 \tag{41}$$

Biomass from Fields to New Biorefineries. The biomass transportation cost from the fields to new biorefineries involves a capital cost for the new infrastructure (new highways and roads) ($C_{b2}^{\text{Captrans-biomass}}$) and an operational transportation cost ($C_{b2}^{\text{optrans-biomass}}$). The first one is equal to a fixed transportation cost ($F_{bm,m,b2}^{\text{cost-trans-biomass}}$) multiplied by the binary variable to determine if the new infrastructure is required ($y_{bm,m,b2}^{\text{trans-biomass}}$), as well as a variable cost ($V_{bm,m,b2}^{\text{cost-trans-biomass}}$) multiplied by the amount of transported biomass ($f_{bm,m,b2}^{\text{biomass1}}$) elevated to an exponent ($\gamma_{b2}^{\text{trans-biorl}}$). The second one is equal to the sum of a unitary transportation cost for biomass from fields to new biorefineries ($\text{UC}_{bm,m,b2}^{\text{trans-biomass-new}}$) multiplied by the annual amount of transported biomass between these entities of the supply chain ($H_Y \cdot f_{bm,m,b2}^{\text{biomass1}}$). Consequently, the total biomass transportation cost from the fields to new biorefineries ($C_{b2}^{\text{trans-biomass-new}}$) is equal to sum of the capital ($C_{b2}^{\text{Captrans-biomass}}$) and operational transportation cost ($C_{b2}^{\text{optrans-biomass}}$):

$$C_{b2}^{\text{Captrans-biomass}} = \sum_{m}\sum_{bm} K_F \cdot (F_{bm,m,b2}^{\text{cost-trans-biomas}} \cdot y_{bm,m,b2}^{\text{trans-biomass}} + V_{bm,m,b2}^{\text{cost-trans-biomass}} \cdot (f_{bm,m,b2}^{\text{biomass1}})^{\gamma_{b2}^{\text{trans-biorl}}}), \quad \forall\ b2 \tag{42}$$

$$C_{b2}^{\text{optrans-biomass}} = \sum_{m}\sum_{bm} \text{UC}_{bm,m,b2}^{\text{trans-biomass-new}} \cdot (H_Y \cdot f_{bm,m,b2}^{\text{biomass1}}), \quad \forall\ b2 \tag{43}$$

$$C_{b2}^{\text{trans-biomass-new}} = C_{b2}^{\text{Captrans-biomass}} + C_{b2}^{\text{optrans-biomass}}, \quad \forall\ b2 \tag{44}$$

The binary variables for the biomass transportation activity from the fields to new biorefineries ($y_{bm,m,b2}^{\text{trans-biomass}}$) is activated when the amount of transported biomass from the suppliers to the new biorefineries ($f_{bm,m,b2}^{\text{biomass1}}$) is between an upper limit ($\text{fl}_{bm,m,b2}^{\text{biomass-MAX}}$) and a lower limit ($\text{fl}_{bm,m,b2}^{\text{biomass-MIN}}$). Then, the transported biomass between suppliers and new biorefineries ($f_{bm,m,b2}^{\text{biomass1}}$) is greater than the minimum limit ($\text{fl}_{bm,m,b2}^{\text{biomass-MIN}}$) multiplied by the binary variable associated with the biomass transportation ($y_{bm,m,b2}^{\text{trans-biomass}}$) and lower than the maximum limit ($\text{fl}_{bm,m,b2}^{\text{biomass-MAX}}$) multiplied by the same binary variable ($y_{bm,m,b2}^{\text{trans-biomass}}$):

$$\text{fl}_{bm,m,b2}^{\text{biomass-MIN}} \cdot y_{bm,m,b2}^{\text{trans-biomass}} \le f_{bm,m,b2}^{\text{biomass1}} \le \text{fl}_{bm,m,b2}^{\text{biomass-MAX}} \cdot y_{bm,m,b2}^{\text{trans-biomass}}, \quad \forall\ bm, \forall\ m, \forall\ b2 \tag{45}$$

Products from New Biorefineries to Distribution Centers. The total transportation cost for bioproducts from new biorefineries to distribution centers ($C_{b2}^{\text{trans-product-bioref-new}}$) includes the capital cost for new infrastructure (pipelines, highways; $C_{b2}^{\text{Captrans-product-bioref}}$) and the operational cost for transportation ($C_{b2}^{\text{optrans-product-bioref}}$). On this regard, the capital cost for transportation ($C_{b2}^{\text{Captrans-product-bioref}}$) is given by a fixed cost ($F_{p2,b2,j}^{\text{cost-trans-prod-bioref}}$) multiplied by a binary variable for this activity ($y_{p2,b2,j}^{\text{trans-prod-bioref}}$) plus a variable cost ($V_{p2,b2,j}^{\text{cost-trans-prod-bioref}}$) multiplied by the transported amount of product ($f_{p2,b2,j}^{\text{product-biorefl}}$) elevated to an exponent ($\gamma_{b2}^{\text{trans-bior2}}$). It should be noted that all capital costs must be annualized through the factor K_F. Additionally, the operational cost for transportation of products ($C_{b2}^{\text{optrans-product-bioref}}$) is equal to a unitary operational cost ($\text{UC}_{p2,b2,j}^{\text{trans-prod-bior-new}}$) multiplied by the annual transported

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amount of bioproducts $(H_Y \cdot f_{p2,b2,j}^{\text{product-bioref1}})$:

$$C_{b2}^{\text{Captrans-product-bioref}} = \sum_{p2}\sum_{j} K_F \cdot \left(F_{p2,b2,j}^{\text{cost-trans-prod-bioref}} \cdot y_{p2,b2,j}^{\text{trans-prod-bioref}} + V_{p2,b2,j}^{\text{cost-trans-prod-bioref}} \cdot (f_{p2,b2,j}^{\text{product-bioref1}})^{y_{b2}^{\text{trans-bioref}}}\right), \quad \forall\, b2 \tag{46}$$

$$C_{b2}^{\text{optrans-product-bioref}} = \sum_{p2}\sum_{j} \text{UC}_{p2,b2,j}^{\text{trans-prod-bior-new}} \cdot (H_Y \cdot f_{p2,b2,j}^{\text{product-bioref1}}), \quad \forall\, b2 \tag{47}$$

$$C_{b2}^{\text{trans-product-bioref-new}} = C_{b2}^{\text{Captrans-product-bioref}} + C_{b2}^{\text{optrans-product-bioref}}, \quad \forall\, b2 \tag{48}$$

The binary variable for transporting bioproducts from new refineries to distribution centers $(y_{p2,b2,j}^{\text{trans-prod-bioref}})$ is activated when the transported amount of product $(f_{p2,b2,j}^{\text{product-bioref1}})$ is lower than the upper limit $(\text{fl}_{p2,b2,j}^{\text{product-bioref-MAX}})$ and greater than the lower limit $(\text{fl}_{p2,b2,j}^{\text{product-bioref-MIN}})$:

$$\text{fl}_{p2,b2,j}^{\text{product-bioref-MIN}} \cdot y_{p2,b2,j}^{\text{trans-prod-bioref}} \le f_{p2,b2,j}^{\text{product-bioref1}} \le \text{fl}_{p2,b2,j}^{\text{product-bioref-MAX}} \cdot y_{p2,b2,j}^{\text{trans-prod-bioref}}, \quad \forall\, p2, \forall\, b2, \forall\, j \tag{49}$$

Emissions per Activity and Facility. This section presents the total emissions associated with the supply chain, which includes the following sections.

Emissions for Extracting Oil for Refineries. The equivalent emissions of CO_2 for oil extraction $(E_i^{\text{oil-ext}})$ are equal to the sum of the unitary equivalent emissions of CO_2 for oil extraction $(\beta_{o,i}^{CO_2\text{-ext}})$ multiplied by the flow of oil obtained from the wells $(f_{o,i}^{\text{oil1}})$ and the operating days (H_Y):

$$E_i^{\text{oil-ext}} = \sum_{o} \beta_{o,i}^{CO_2\text{-ext}} \cdot (H_Y \cdot f_{o,i}^{\text{oil1}}), \quad \forall\, i \tag{50}$$

Emissions for the Refinery Production. The equivalent emissions of CO_2 for oil refining $(E_i^{\text{product-ref}})$ are equal to the sum of the unitary equivalent emissions of CO_2 for the oil refining $(\beta_{p1,i}^{CO_2\text{-product-ref}})$ multiplied by the total flow of products from refineries $(F_{p1,i}^{\text{product-ref}})$ and the operating days (H_Y):

$$E_i^{\text{product-ref}} = \sum_{p1} \beta_{p1,i}^{CO_2\text{-product-ref}} \cdot (H_Y \cdot F_{p1,i}^{\text{product-ref}}), \quad \forall\, i \tag{51}$$

Emissions for Transportation of Products from Refineries to Distribution Centers. The equivalent emissions of CO_2 for transportation of products from refineries to distribution centers $(E_i^{\text{trans-product-ref}})$ are equal to the sum of the unitary equivalent emissions of CO_2 produced by the transportation of products from refineries to the distribution centers $(\beta_{p1,i,j}^{CO_2\text{-trans-product-ref}})$ multiplied by the amount of distributed products from refineries to distribution centers, taken into account the operating days to get an annual base $(H_Y \cdot f_{p1,i,j}^{\text{product-ref1}})$:

$$E_i^{\text{trans-product-ref}} = \sum_{j}\sum_{p1} \beta_{p1,i,j}^{CO_2\text{-trans-product-ref}} \cdot (H_Y \cdot f_{p1,i,j}^{\text{product-ref1}}), \quad \forall\, i \tag{52}$$

Emissions by the Use of Products from Oil As Fuels. The equivalent emissions of CO_2 obtained from burning of petroleum fuels $(E_i^{\text{uses-product-ref}})$ involve the sum of the unitary equivalent emissions of CO_2 $(\beta_{p1,i}^{CO_2\text{-use-product-ref}})$, the total flow of products from refineries $(F_{p1,i}^{\text{product-ref}})$, and the operating days to get an annual basis (H_Y):

$$E_i^{\text{use-product-ref}} = \sum_{p1} \beta_{p1,i}^{CO_2\text{-use-product-ref}} \cdot (H_Y \cdot F_{p1,i}^{\text{product-ref}}), \quad \forall\, i \tag{53}$$

Emissions of CO_2 Sequestrated by Biomass Growth. The emissions of CO_2 are captured when biomass is growing in the cultivation fields, therefore, the captured emissions of CO_2 by the biomass growth $(\text{NE}_b^{\text{biomass-growth}})$ is equal to the sum of the unitary equivalent emissions of CO_2 for the biomass production $(\gamma_{bm,b}^{CO_2\text{-biomass-growth}})$ multiplied by the total amount of biomass in biorefineries $(f_{bm,b}^{\text{biomass}})$ and the operating days (H_Y):

$$\text{NE}_b^{\text{biomass-growth}} = \sum_{bm} \gamma_{bm,b}^{CO_2\text{-biomass-Growth}} \cdot (H_Y \cdot F_{bm,b}^{\text{biomass}}), \quad \forall\, b \tag{54}$$

It should be noticed that the factor depends on the considered horizon of time. For this case, the horizon of time is equal to 1 year and the life cycle of the bioresources is fully completed. For that reason, the captured emissions can be associated with a global factor, which involves all the stage of the biomass growth.

Emissions for Transporting Biomass from Fields to Biorefineries. The emissions of CO_2 for biomass transportation $(E_b^{\text{biomass-trans}})$ take into account the sum of unitary equivalent emissions of CO_2 for biomass transportation $(\gamma_{bm,m,b}^{CO_2\text{-biomass-trans}})$ multiplied by the amount of biomass that is distributed from the biomass cultivation field to biorefineries $(f_{bm,m,b}^{\text{biomass1}})$ and the operating days (H_Y):

$$E_b^{\text{biomass-trans}} = \sum_{m}\sum_{bm} \gamma_{bm,m,b}^{CO_2\text{-biomass-trans}} \cdot (H_Y \cdot f_{bm,m,b}^{\text{biomass1}}), \quad \forall\, b \tag{55}$$

Emissions for Biorefinery Production. The emissions of CO_2 associated with the production in biorefineries $(E_b^{\text{bioref-product}})$ are equal to the sum of the unitary equivalent emissions of CO_2 for the production of bioproducts $(\gamma_{p2,bm,b}^{CO_2\text{-bioref-prod}})$ multiplied by the total amount of biomass in biorefineries $(f_{bm,b}^{\text{biomass}})$ and the operating days:

$$E_b^{\text{bioref-product}} = \sum_{bm}\sum_{p2} \gamma_{p2,bm,b}^{CO_2\text{-bioref-prod}} \cdot (H_Y \cdot F_{bm,b}^{\text{biomass}}), \quad \forall\, b \tag{56}$$

Emissions for Transportation of Bioproducts from Biorefineries to Distribution Centers. The emissions associated with the transportation of bioproducts from biorefineries to distribution centers $(E_b^{\text{trans-prod-bioref}})$ involve the sum of the products of unitary equivalent emissions of CO_2 for transporting bioproducts $(\gamma_{p2,b,j}^{CO_2\text{-trans-prod-bioref}})$, the distributed bioproducts from biorefineries to distribution centers $(f_{p2,b,j}^{\text{product-bioref1}})$ and operating days:

$$E_b^{\text{trans-prod-bioref}} = \sum_{j}\sum_{p2} \gamma_{p2,b,j}^{CO_2\text{-trans-prod-bioref}} \cdot (H_Y \cdot f_{p2,b,j}^{\text{product-bioref1}}), \quad \forall\, b \tag{57}$$

Emissions for Use of the Products from Biomass as Biofuels. The emissions of CO_2 derived for the use of bioproducts $(E_b^{\text{use-prod-bioref}})$ account for the sum of the unitary equivalent emissions of CO_2 for the burned bioproducts

($\gamma_{p2,b}^{CO_2\text{-use-prod-bioref}}$), the total flow rate of bioproducts from biorefineries ($F_{p2,b}^{\text{product-bioref}}$) and operating days:

$$E_b^{\text{use-prod-bioref}} = \sum_{p2} \gamma_{p2,b}^{CO_2\text{-use-prod-bioref}} \cdot (H_Y \cdot F_{p2,b}^{\text{product-bioref}}), \quad \forall\ b \tag{58}$$

Total Emissions Per Refinery. The total emissions associated with refineries ($\text{Em}_i^{\text{refinery}}$) include the emissions produced in each one of the activities involved in the refinery. These are CO_2 emissions for oil extraction $E_i^{\text{oil-ext}}$, emissions of CO_2 for oil refining ($E_i^{\text{product-ref}}$), CO_2 emissions for transportation of products from oil ($E_i^{\text{trans-product-ref}}$), and emissions of CO_2 obtained from burning of petroleum fuels ($E_i^{\text{use-product-ref}}$):

$$\text{Em}_i^{\text{refinery}} = E_i^{\text{oil-ext}} + E_i^{\text{product-ref}} + E_i^{\text{trans-product-ref}} + E_i^{\text{use-product-ref}}, \quad \forall\ i \tag{59}$$

Total Biorefinery Emissions. The total emissions of biorefineries ($\text{Em}_b^{\text{bioref}}$) include the emissions for each one of the activities involved in biorefineries such as the emissions of CO_2 for biomass transportation ($E_b^{\text{biomass-trans}}$), emissions of CO_2 due to production in biorefineries ($E_b^{\text{bioref-product}}$), emissions produced by the transportation of bioproducts from biorefineries to distribution centers ($E_b^{\text{trans-prod-bioref}}$), emissions of CO_2 derived of the use of bioproducts ($E_b^{\text{use-prod-bioref}}$), and the captured emissions of CO_2 by the biomass growth in cultivation sites ($\text{NE}_b^{\text{biomass-growth}}$):

$$\text{Em}_b^{\text{bioref}} = E_b^{\text{biomass-trans}} + E_b^{\text{bioref-product}} + E_b^{\text{trans-prod-bioref}} + E_b^{\text{use-prod-bioref}} - \text{NE}_b^{\text{biomass-growth}}, \quad \forall\ b \tag{60}$$

Emissions for Capturing CO_2 by Eco-industries. The emissions of CO_2 captured by the eco-industries ($\text{Em}_e^{\text{ecoind}}$) are given by the unitary amount of emissions of CO_2 for eco-industries that is a factor to capture CO_2 per tree ($\gamma_e^{\text{emissionecoind}}$) multiplied by the total number of trees for each eco-industry (N_{Te}):

$$\text{Em}_e^{\text{ecoind}} = \gamma_e^{\text{emissionecoind}} \cdot N_{Te}, \quad \forall\ e \tag{61}$$

It is important to mention that the trees' life cycles are longer than the considered horizon of time and the captured emissions can change drastically during the complete life cycle. Nevertheless, the change of the captured emissions in the horizon of time is so small. For that reason, the factor to obtain the captured emissions for the forest plantations is considered to be constant. For this case, the considered capturing factor is assumed as an average of the tree capacity to capture emissions. In addition, the sum of CO_2 emissions captured by eco-industries are equal to the sum of captured CO_2 emission from refineries by eco-industries ($\text{Emcap}_i^{\text{refinery}}$) plus the sum of captured CO_2 emissions from biorefineries by eco-industries ($\text{Emcap}_b^{\text{biorefinery}}$):

$$\sum_e \text{Em}_e^{\text{ecoind}} = \sum_i \text{Emcap}_i^{\text{refinery}} + \sum_b \text{Emcap}_b^{\text{biorefinery}} \tag{62}$$

Equations for Demand of Products. *Demand of Diesel.* The demand of diesel is covered by the diesel produced in refineries ($f_{p1,i,j}^{\text{product-ref1}}$) as well as the biodiesel produced in biorefineries ($f_{p2,b,j}^{\text{product-bioref1}}$):

$$H_Y \cdot \text{Demand}_j^{\text{diesel}} = \sum_i \sum_{p1} H_Y \cdot f_{p1,i,j}^{\text{product-ref1}} + \sum_b \sum_{p2} H_Y \cdot f_{p2,b,j}^{\text{product-bioref1}}, \quad \forall\ j,\ p1 \in \text{diesel},\ p2 \in \text{biodiesel} \tag{63}$$

Demand of Gasoline. The demand of gasoline is covered by the gasoline produced in refineries ($f_{p1,i,j}^{\text{product-ref1}}$) and the bioethanol produced in biorefineries ($f_{p2,b,j}^{\text{product-bioref1}}$):

$$H_Y \cdot \text{Demand}_j^{\text{gasoline}} = \sum_i \sum_{p1} H_Y \cdot f_{p1,i,j}^{\text{product-ref1}} + \sum_b \sum_{p2} H_Y \cdot f_{p2,b,j}^{\text{product-bioref1}}, \quad \forall\ j,\ p1 \in \text{gasoline},\ p2 \in \text{bioethanol} \tag{64}$$

Equations for Jobs. *Generated Jobs in New Refineries.* The jobs in refineries include the processing and installation jobs only in new refineries, it is important to mention that the jobs for transportation were given in the transportation network to existing refineries:

$$\text{Jobs}^{\text{refinery}} = H_Y \cdot \sum_{i2} \text{JobsUnit}_{i2}^{\text{ref}} \cdot (f_{i2}^{\text{oil}}) \tag{65}$$

Jobs Generated in New Biorefineries. The jobs in biorefineries include the ones generated for biomass plantations, transportation of biomass, installing and processing in new biorefineries.

$$\text{Jobs}^{\text{bioref}} = H_Y \cdot \sum_{bm,m} \text{JobsUnit}_{bm,m}^{\text{biomplat}} \cdot F_{bm,m}^{\text{biomass-field}} + H_Y \cdot \sum_{bm,m,b} \text{JobsUnit}_{bm,m,b}^{\text{biomtrans}} \cdot f_{bm,m,b}^{\text{biomass1}} + H_Y \cdot \sum_{bm,b} \text{JobsUnit}_{bm,b}^{\text{biombioref}} \cdot F_{bm,b}^{\text{biomass}} \tag{66}$$

Generated Jobs in Forest Plantations. In case of forest eco-industries, the jobs considered correspond to people needed to take care of forest plantations.

$$\text{Jobs}^{\text{ecoind}} = \sum_e \text{JobsUnit}_e^{\text{ecoind}} \cdot N_{Te} \tag{67}$$

Objective Functions. The mathematical model considers three different objective functions, which are described as follows.

Economic Objective Function. The economic objective function considers the maximization of the total profit (EOF). The total profit involves the sum of the profit from refineries ($\text{Profit}^{\text{refinery}}$), biorefineries ($\text{Profit}^{\text{bioref}}$), and eco-industries ($\text{Profit}^{\text{ecoind}}$):

$$\max\{\text{EOF} = \text{Profit}^{\text{refinery}} + \text{Profit}^{\text{bioref}} + \text{Profit}^{\text{ecoind}}\} \tag{68}$$

Environmental Objective Function. The environmental objective function aims to minimize the total CO_2 emissions (NetEmission), which consider the sum of total emissions from refineries ($\text{Em}_i^{\text{refinery}}$) and biorefineries ($\text{Em}_b^{\text{bioref}}$) minus the emissions captured by forest plantations ($\text{Em}_e^{\text{ecoind}}$):

$$\min\{\text{NetEmission} = \sum_i \text{Em}_i^{\text{refinery}} + \sum_b \text{Em}_b^{\text{bioref}} - \sum_e \text{Em}_e^{\text{ecoind}}\} \tag{69}$$

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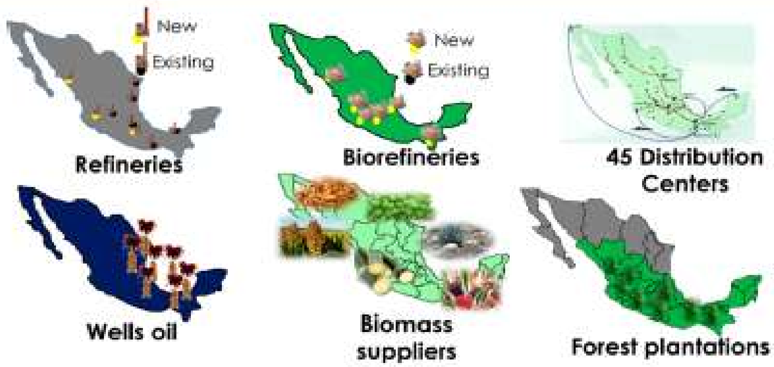

Figure 2. General representation for the case study.

Social Objective Function. The social objective function considers the maximization of the total generated jobs (TOTALJOBS) to implement the proposed scheme. This objective function consists in the sum of number of generated jobs in refineries ($Jobs^{refinery}$), biorefineries ($Jobs^{bioref}$), and forest plantations ($Jobs^{ecoind}$).

$$\max\{TOTALJOBS = Jobs^{refinery} + Jobs^{bioref} + Jobs^{ecoind}\} \quad (70)$$

CASE STUDY

A case study from Mexico is presented to show the applicability of the proposed approach. Figure 2 shows schematically the different localization for the facilities involved in the case study. The main considerations about localization are described as follow:

Refineries. Six existing refineries are taken into account, which currently exist in the energy system of Mexico; also it is considered the possibility to install three new refineries. Table 1 shows the localization for the considered refineries.

Table 1. Localization of Refineries for the Case Study

existing refineries	new refineries
Cadereyta	Toluca
Ciudad Madero	Guadalajara
Minatitlán	Mazatlán
Salamanca	
Salina Cruz	
Tula	

It is worth to note that the allocation of new refineries is based on the demands and existing infrastructure to transport raw materials and products. For instance, the refinery of Toluca is considered because there is a huge demand of fuels in the central part of the country.

Biorefineries. The possibility to install six new biorefineries is considered, which would be allocated in Guadalajara, Celaya, Morelia, Mazatlán, Veracru,z and Chiapas; these places were chosen because there is infrastructure to transport products and the available raw materials.

Distribution Centers. There are considered 45 distribution centers; these correspond to the storage and distribution terminals of PEMEX (The Mexican Company of Petroleum) allocated in the Mexican territory.

Biomass Suppliers. The different states of the country are considered as supplier of biomass, accounting for the available biomass and the existing infrastructure.

Oil wells. The oil wells considered are production places of petroleum stated by PEMEX, which are Territorial waters, Tabasco, Veracruz, Chiapas, Puebla, Tamaulipas, and San Luis Potosí.

Forest Plantations. For the case of forest plantations, it is taken into account the possibility to install one of them per state of the country, their size and existence depend on the availability of land. Most locations are at the north and center part of country, as Mexico City does not have suitable surface land and proper climatic conditions to develop forest plantations.

It is important to note that the data about the production and processing of oil were obtained from PEMEX.[46] Additionally, there are considered different types of raw materials (biomass and oil) and products (bioproducts and petroleum products); these are presented in Table 2. The data for the availability of biomass were obtained from SAGARPA,[47] and these are presented in Table 3.

Table 2. Products and Raw Materials for the Case Study

types of biomass	bioproducts	type of petroleum	petro-products
woodchips		petroleum	gasoline PEMEX magna
sugar cane	bioethanol		
sweet sorghum			gasoline PEMEX premium
jatropha	biodiesel		
african palm			
waste of agave			PEMEX diesel

It is worth noting that according with diverse works about the production of biofuels from biomass,[22,23] the current biomass production is not enough to meet the fuel demands. However, there is a great opportunity to increase the biofuel production through the consideration of additional raw materials or expanding the cultivated area. In this context, the data for the production per unit area have been included in Table 4. On the other hand, the data about production of bioproducts were obtained from the reports by Santibañez-Aguilar et al.[23] and Murillo-Alvarado et al.[22,48] Also, the data for the production from oil were obtained from PEMEX.[46] In this sense, the corresponding data for the capacity of procesing plants and unitary costs are presented in Tables 5 and 6. The data for the forest plantations are the absorption capacity of CO_2, operating and capital costs, and these are included in Table 7. It is important to note that the data for capturing the CO_2 per area of tree were obtained from Plantinga and Mauldin.[49]

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Table 3. Availability of Raw Material Per Supply Place

supply place	woodchip (ton/day)	sugar cane (ton/day)	sweet sorghum (ton/day)	jatropha (ton/day)	african palm (ton/day)	waste of agave (ton/day)
Aguascalientes	22.47	0.00	55.58	0.00	0.00	0.00
Baja California	22.59	0.00	671.38	0.00	0.00	0.00
BC Sur	22.59	0.00	15.09	0.00	0.00	0.00
Campeche	7.56	1538.98	0.00	0.00	65.57	0.00
Coahuila	22.47	0.00	2560.17	0.00	0.00	0.00
Colima	17.65	3253.91	60.43	0.00	0.00	12.33
Chiapas	7.56	6424.89	9.64	0.00	838.45	0.00
Chihuahua	22.47	0.00	1397.03	0.00	0.00	0.00
Mexico City	0.00	0.00	0.00	0.00	0.00	0.00
Durango	22.59	0.00	1809.81	0.00	0.00	0.48
Guanajuato	17.65	0.00	8.99	0.00	0.00	172.07
Guerrero	17.65	0.00	324.99	0.00	0.00	10.26
Hidalgo	4.15	0.00	0.00	0.00	0.00	0.00
Jalisco	17.65	16224.66	798.49	0.00	0.00	1565.77
State of Mexico	5.19	0.00	13.42	0.00	0.00	10.04
Michoacán de Ocampo	17.65	3748.23	518.13	0.00	0.00	110.41
Morelos	5.19	4583.93	28.03	0.00	0.00	9.25
Nayarit	22.59	5036.72	140.75	0.00	0.00	52.15
Nuevo León	22.47	0.00	293.52	0.00	0.00	0.00
Oaxaca	7.56	10356.27	13.03	0.00	0.00	181.30
Puebla	4.15	4640.73	0.00	0.00	0.00	32.60
Querétaro	5.19	0.00	18.48	0.00	0.00	0.87
Quintana Roo	7.56	4152.21	0.00	0.00	0.00	1.24
San Luis Potosí	4.15	10936.62	33.51	0.00	0.00	0.07
Sinaloa	22.59	4031.99	614.30	0.00	0.00	0.20
Sonora	22.59	0.00	705.22	0.00	0.00	0.00
Tabasco	7.56	4106.02	0.00	0.00	204.43	0.00
Tamaulipas	4.15	8108.21	61.00	0.00	0.00	171.62
Tlaxcala	5.19	0.00	0.00	0.00	0.00	0.00
Veracruz	4.15	46954.33	78.07	0.00	135.51	0.00
Yucatán	7.56	0.00	35.21	3.74	0.00	0.00
Zacatecas	22.47	0.00	225.09	0.00	0.00	0.00

Besides, the case study considers diverse ways to account for the number of created jobs. These jobs are associated with unitary jobs for each activity (processing, growing of trees, raw material production, and others). The paper uses several sources for computing the number of generated jobs. The jobs for the biomass production were calculated through the Jobs and Economic Development Impact method (JEDI[50]) and the IMPLAN model (IMPLANT[51]). Additionally, some data for the number of jobs were reported by Santibañez-Aguilar et al.[23] On the other hand, the jobs in the chemical plants were obtained from reports provided by PEMEX.[46] Additionally, the generated jobs for the forest plantations were based on the area to be cared per person and the minimum salary reported by the Internal Revenue Service of Mexico (SAT[52]). It should be noted that the coefficients are different for the forest plantations and the chemical plants.

RESULTS

The muti-objective mixer integer non linear programing model was coded in the software GAMS.[53] It should be noticed that the values of the exponents in the capital cost eqs (eqs 6, 19, and 32) produce a linear behavior because the exponents are equal to 1 and the model was solved as a mixed-integer linear programming problem avoiding numerical complications. The mathematical formulation consists of 2159 binary variables, 5818 continuous variables, and 5306 constraints. The model was solved in a computer with an i7 processor and 16 GB of RAM, maximizing the net annual profit and the number of new generated jobs and minimizing the total CO_2 emissions. In this regard, the *ε-constraint* method was implemented.[54]

The application of the *ε-constraint* method generated a first Pareto curve, which is shown in Figure 3. The CPU time to obtain each solution of the Pareto curve was approximately 0.97 s. This figure shows the most profitable solution, which corresponds to the largest net emissions and the most environmentally friendly solution, as well as the lowest profit. It is worth noting that Figure 3 is useful to illustrate the trade-offs between the environmental and economic objectives. Notice that Figure 3 presents different Pareto curves obtained with a minimum value of the number of jobs, while Figure 4 shows the Pareto curve in three dimensions to illustrate the behavior of the three considered objectives. The Pareto curve in three dimensions is composed of several points, where each of them represents a different combination of state variables of the model, like installation and capacity of refineries, biorefineries and forest plantations, raw material and product flows, etc. Figure 4 shows that the relationship between the number of jobs and emissions is inversely proportional, it means that the number of jobs increases when the amount of emissions decreases. This behavior is because the installation of forest plantations and biorefineries promotes the jobs creation and decreases the net emissions.

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Table 4. Area Needed for Cultivation of Raw Material Per Supply Place

supply place	woodchip (ton/ha)	sugar cane (ton/ha)	sweet sorghum (ton/ha)	jatropha (ton/ha)	african palm (ton/ha)	waste of agave (ton/ha)
Aguascalientes	0.76	0.00	32.79	0.00	0.00	0.00
Baja California	0.76	0.00	34.63	0.00	0.00	0.00
BC Sur	0.76	0.00	57.69	0.00	0.00	0.00
Campeche	0.76	68.94	0.00	0.00	7.8	0.00
Coahuila	0.76	0.00	26.26	0.00	0.00	0.00
Colima	0.76	102.67	27.17	0.00	0.00	1.00
Chiapas	0.76	92.39	21.00	0.00	7.45	0.00
Chihuahua	0.76	0.00	21.51	0.00	0.00	0.00
Mexico City	0.00	0.00	0.00	0.00	0.00	0.00
Durango	0.76	0.00	28.96	0.00	0.00	0.48
Guanajuato	0.76	0.00	15.05	0.00	0.00	7.97
Guerrero	0.76	0.00	24.86	0.00	0.00	3.77
Hidalgo	0.76	0.00	0.00	0.00	0.00	0.00
Jalisco	0.76	96.22	22.54	0.00	0.00	9.33
State of Mexico	0.76	0.00	32.62	0.00	0.00	6.90
Michoacán de Ocampo	0.76	93.00	27.56	0.00	0.00	9.13
Morelos	0.76	121.15	39.31	0.00	0.00	8.20
Nayarit	0.76	62.50	22.95	0.00	0.00	6.57
Nuevo León	0.76	0.00	14.70	0.00	0.00	0.00
Oaxaca	0.76	71.85	29.26	0.00	0.00	5.85
Puebla	0.76	81.56	0.00	0.00	0.00	9.30
Querétaro	0.76	0.00	23.58	0.00	0.00	0.50
Quintana Roo	0.76	64.80	0.00	0.00	0.00	2.00
San Luis Potosí	0.76	73.23	21.58	0.00	0.00	2.50
Sinaloa	0.76	80.14	6.66	0.00	0.00	0.20
Sonora	0.76	0.00	23.54	0.00	0.00	0.00
Tabasco	0.76	73.83	0.00	0.00	204.43	0.00
Tamaulipas	0.76	84.55	12.49	0.00	0.00	3.52
Tlaxcala	0.76	0.00	0.00	0.00	0.00	0.00
Veracruz	0.76	72.45	30.79	0.00	135.51	0.00
Yucatán	0.76	0.00	21.08	0.75	0.00	0.00
Zacatecas	0.76	0.00	20.39	0.00	0.00	0.00

Table 5. Unit Capital and Operating Costs for Refineries

unit variable capital cost ($US/ton·y)	unit fixed capital cost ($US)	unit operating cost ($US/ton)
84.87	1000000000	169.73

The Pareto curve of Figure 4 provides values for the three objectives, which are associated with a supply chain configuration; therefore, two points were selected to compare the value of the objectives to different solutions. Point A represents

Table 6. Capacities and Unitary Costs of Refineries and Biorefineries

data for biorefineries				
raw material	operating cost ($US/ton)	variable capital cost ($US/ton·y)	fixed capital cost (million $US)	processing capacity (ton/day)
woodchip	100	0.10	628.60	18554
sugar cane	39.52	0.04	628.60	18554
sweet sorghum	20.93	0.02	628.60	18554
jatropha	113.31	0.11	628.60	18554
african palm	71.56	0.07	628.60	18554
waste of agave	266.60	0.28	628.60	18554
data for refineries				
Cadereyta	169.73			34341
Ciudad Madero	169.73			23610
Minatitlán	169.73			33250
Salamanca	169.73			35378
Salina Cruz	169.73			51367
Tula	169.73			44710
Toluca	169.73	169.73	1000	37109
Guadalajara	169.73	169.73	1000	37109
Mazatlán	169.73	169.73	1000	37109

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Table 7. Data to Forest Plantations

concept	value
operating cost ($US/tree)	0.30
variable capital cost ($US/tree)	0.30
fixed capital cost ($US)	302
employees per tree (people/tree)	1.8906×10^{-4}
used land per tree (ha/tree)	7.5625×10^{-4}
cost per captured emissions for refineries ($US/ton)	10
cost per captured emissions for biorefineries ($US/ton)	5

the solution for the maximum profit, where all possible refineries were selected to satisfy the fuel demand and no forest plantation or biorefinery were selected. In addition, the solution of point A yields around 38 000 jobs. On the other hand, Point B shows a profit equal to $24,534 M $US, a value of net emissions equal to 16.8×10^3 tons of CO_2 and 744 318 jobs per year; these values are obtained through the installation of 8 forest plantations, 2 biorefineries, and 8 refineries. It is important to note that the values at point B indicate that biorefineries produce less emission than refineries because the system tries to reduce the net emissions via installing new biorefineries. Also, the proportion of decreasing is not equal to forest plantation and biorefineries, for example by comparing Points A and B, the forest plantations reduce 440×10^6 tons of CO_2 and the biorefineries reduce 77×10^6 tons of CO_2 (see Table 8).

Additionally, Table 9 compares the number of jobs between Points A and B of Figure 4. It is possible to note that the number of jobs increases significantly because of the installation and operation of forest plantations. Also, the number of jobs per refineries changes from 38 399 jobs to 41 175 jobs, which occurs because some refineries augment their production and biorefineries increase the number of jobs to 1805.

On the other hand, Table 10 shows that the improvement in the number of jobs is because of the increment of production in the refinery of Mazatlan from 78% to 98%. At point B there are

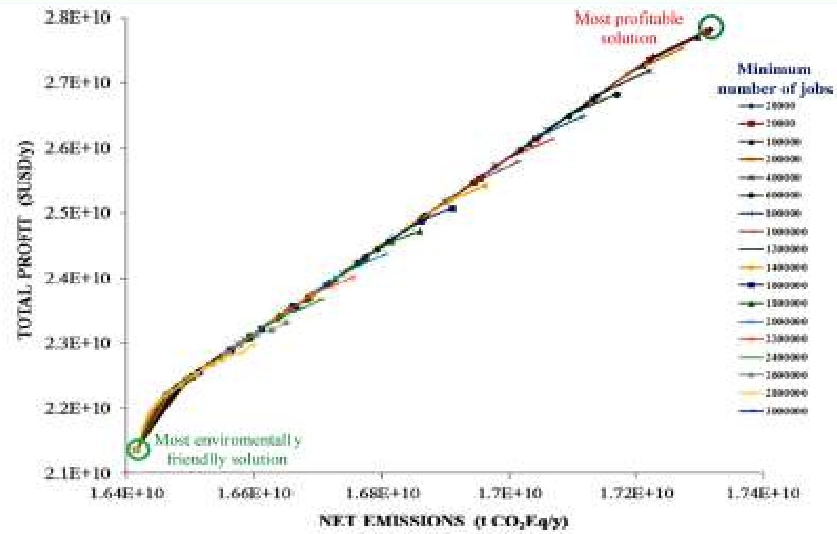

Figure 3. Pareto curves of total emissions and annual net profit.

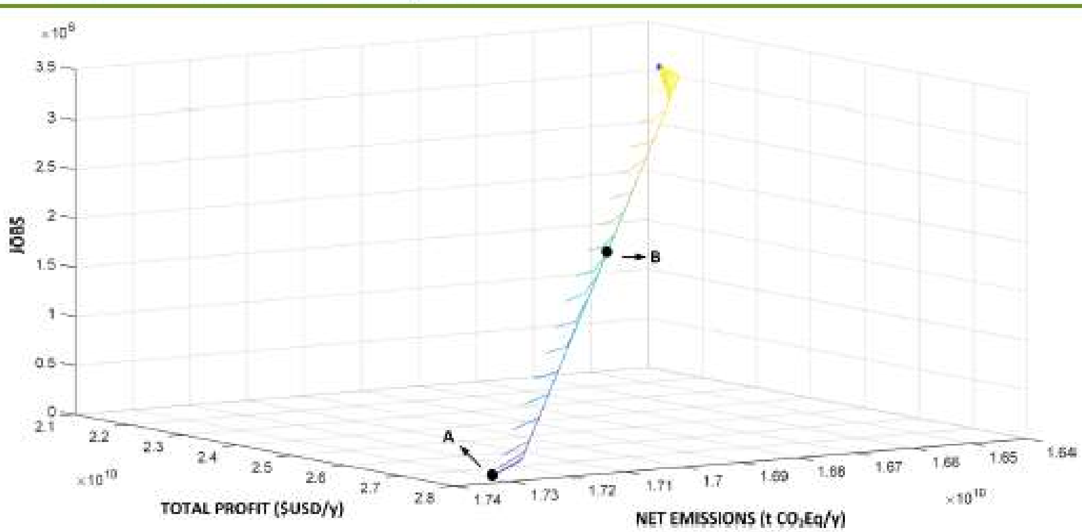

Figure 4. Pareto curves of net emissions, jobs, and annual profit.

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Table 8. Emission Results

solution	net emissions (million ton/y)	decrement of emission through forest plantations (million ton/y)	decrement of emission through biorefineries (million ton/y)
Point A	17317	0	0
Point B	16800	440	77

Table 9. Generated Jobs

facility	Point A	Point B
refineries	38399	41175
biorefineries	0	1805
forest plantations	0	1701300

Table 10. Amount of Processed Oil Per Refinery for Points A and B

	Point B		Point A	
refinery	processed oil (ton/day)	% capacity of plant	processed oil (ton/day)	% capacity of plant
Cadereyta	34342	100	34342	100
Cd. Madero	23610	100	23610	100
Minatitlán	33251	100	33251	100
Salamanca		0	8709	25
Salina Cruz	51367	100	51367	100
Tula Hidalgo	44710	100	44710	100
Toluca	37110	100	37110	100
Guadalajara	37110	100	37110	100
Mazatlán	36435	98	28976	78
total	297935		299185	

jobs due to the installation of a new refinery and the increase in the oil refining, while the Salamanca's refinery decreases from 25% to 0—this refinery only takes into account the job creation for processed oil as it is shown in Table 10.

For the case of the forest plantations, Table 11 shows the amount of trees as well as the captured amount of CO_2 for each

Table 11. Capacity to Capture of Forest Plantations and Percentage of Contribution

forest plantation	number of trees	emissions captured (ton/y)	% emissions captured
Chiapas	1081181028	52837317	12.01
Durango	1818662967	88878059	20.21
Jalisco	1159005533	56640600	12.88
Oaxaca	1382715958	67573329	15.37
Sinaloa	846011507.9	41344582	9.40
Veracruz	1059280442	51767035	11.77
Yucatán	582894776.3	28486068	6.48
Zacatecas	1057322442	52243648	11.88

forest plantation. It is worth noting that the contribution of captured emissions is different for each forest plantation due to the available land.

With respect to the fuel demand, it is possible to observe that the gasoline and diesel are the main produced fuels. Nevertheless, a small amount of biofuels is produced at Point B of Figure 4. Because of the biofuels can be produced from multiple raw materials, it is needed to present the source and the proportion for the production of each biofuels; which is shown in Table 12.

It should be noticed in Table 12 that there is just one selected raw material at Point B of Figure 4 and it is waste

Table 12. Amount and Percentage of Satisfied Demand for Different Bioproducts at Point B

raw material		product			
type	amount (tons/day)	type	amount (tons/day)	% total demand	% relative production
waste of agave	970	bioethanol	351.6	0.38	100
		biodiesel	0	0	0
others	0	bioethanol	0	0	0
		biodiesel	0	0	0

of agave. This raw material is mainly selected due to its availability and price, and because it has a high convertion factor to ethanol. However, the satisfied demand is only 0.38% of the national demand of oil used as gasoline; in other words, 3.8% in a mix with nine parts of gasoline and one of ethanol, in this sense it is posible to say that the amount of raw material is not anough to satisfy the total demand but is posible to reduce the emissions as it is shown in Table 8.

In addition, Figure 5 presents the distribution of raw maerials to the selected biorefineries at Point B, in this case the biorefineries correspond to the ones of Celaya and Guadalajara. It is important to note that the processing plants work at different capacities. For this case the plant in Celaya processes 60% and the rest is processed in Guadalajara. Also, it is posible to note that the raw material is obtained mainly from the states of the central and occident region of the country (Jalisco, Nayarit, Michoacán, Guanajuato, and Oaxaca) and Tamaulipas. In this sense, the state with the highest contribution is Jalisco, because it has the highest percentage of raw materials to both biorefineries. In addition, it is observed that Celaya's biorefinery uses biomass from Michoacan, and Jalisco's biorefinery uses waste of agave from Nayarit to reduce the costs associated with transportation.

In order to illustrate the economic features for the processing facilities, Figure 6 presents the proportion of economic revenues and expenses of biorefineries; while Figure 7 illustrates the proportion of economic revenues and expenses of refineries. For the case of biorefineries, it can be noted that the highest cost corresponds to capital, operation and biomass production costs. Furthermore, the revenues by selling products are very low because of the considered prices of the biofuels without any incentive. Moreover, recently the biofuel prices have decreased significantly. Also, Figure 6b shows the relationship between the diverse economic incomes and expenses. On the other hand, for the case of refineries the highest costs are associated with the raw material (oil) and the operation. In addition, the revenue by selling products is large and it can support all costs to obtain a significant profit. Figure 7b shows the total proportion of economic incomes and expenses, which confirms that the most significant costs are associated with the oil extraction and the operation. Notice that the cost that the refineries pay to reduce emissions through forest plantations is only a little part of the total expenses. Therefore, the payment to reduce emissions could be augmented and the profit would not be affected significantly. In this way, the quantity of reduced emissions is limited by the size of forest plantations.

Finally, Table 13 presents the results for a sensitivity analysis for different values of the biofuel prices and oil costs. These results represent the optimal values for the economic objective function subject to different upper bounds for the net emissions and a lower bound of 1 million for the number of generated jobs. In this context, the value of the biofuel prices and oil costs

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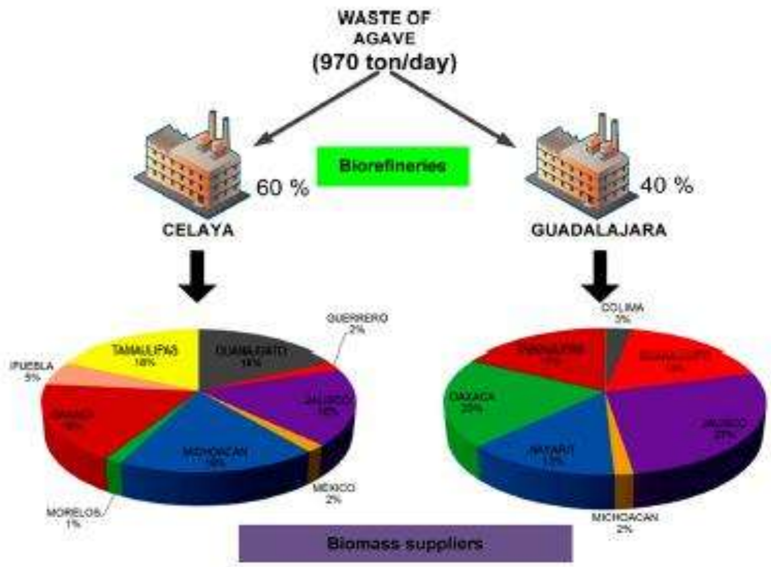

Figure 5. Distribution of raw material in selected biorefineries at Point B.

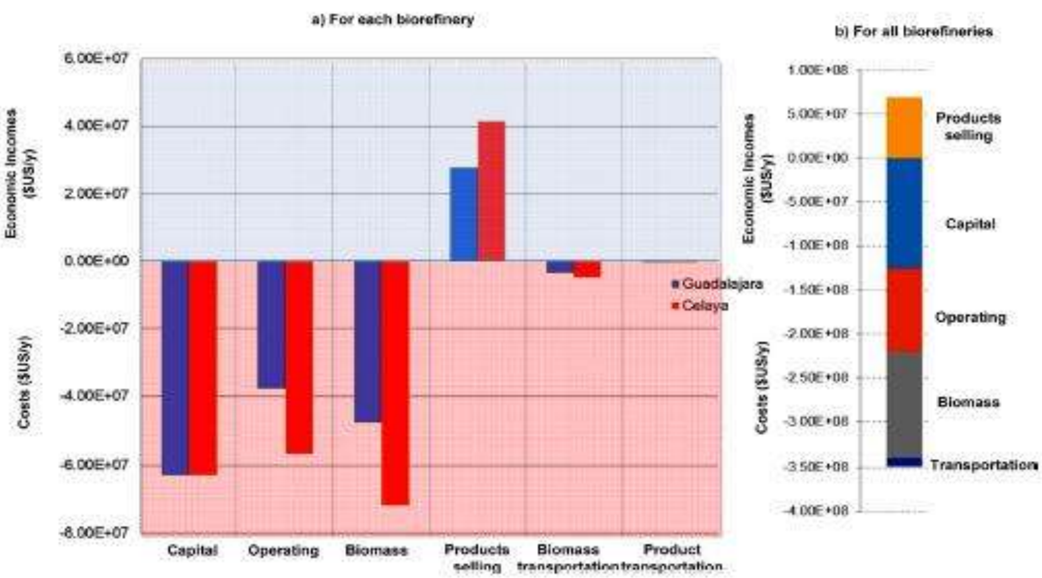

Figure 6. Economic proportion in selected biorefineries at Point B: (a) per biorefinery; (b) for all biorefineries.

were fixed as 1.5, 2, and 3 times the value in the base case. For the case of the biofuel prices can be noted that the effect in the economic objective function is not representative since a variation of 1.5 times the base case does not produce a significant change in the economic objective function; while a variation of 3 times the case produces small augments in the economic objective function. On the other hand, the variations in the oil costs can affect seriously the economic objective function; for instance, an increment of 50% in the oil cost produces changes in the economic objective function from −37.6% up to −45.6% compared with the base case. In addition, if the cost oil is 3 times the cost in the base case, then the economic objective function is negative. Based on the sensitivity analysis, it is possible to state that the proposed system works efficiently with low values of the oil cost because of the system is based on the refining of oil, and the proposed system is drastically affected by the variations in the oil cost.

■ CONCLUSIONS

This paper presented a mathematical programming approach for the optimal configuration of a fuel production system integrated with forest plantations to reduce the overall greenhouse gas emissions. The model incorporates three objective functions (i.e., minimizing the total annual cost, minimizing the greenhouse gas emissions and maximizing the generated jobs), which are presented through a three-dimensional Pareto curve. The proposed optimization model has been applied to a case study from Mexico. The results have shown that the relationship between the environmental and the social objectives is inversely proportional, while the behavior of the economic

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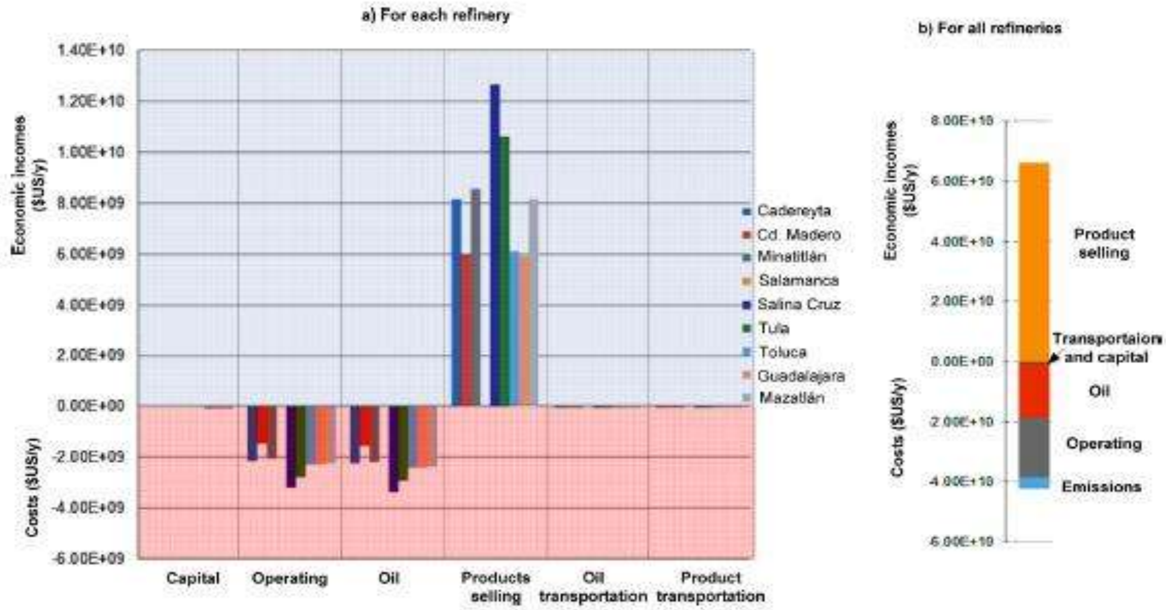

Figure 7. Economic proportion in selected refineries at Point B: (a) per refinery; (b) for all refineries.

Table 13. Sensitivity Analysis for Several Biofuel Prices and Oil Costs

	Biofuel Prices					
	1.5 times base case		2 times base case		3 times base case	
base case (million $US/y)	value (million $US/y)	% change	value (million $US/y)	% change	value (million $US/y)	% change
2.6130×10^4	2.6130×10^4	0.0	2.6130×10^4	0.0	2.6130×10^4	0.0
2.5849×10^4	2.5849×10^4	0.0	2.5915×10^4	0.3	2.5982×10^4	0.5
2.5418×10^4	2.5418×10^4	0.0	2.5487×10^4	0.3	2.5556×10^4	0.5
2.4976×10^4	2.4976×10^4	0.0	2.5045×10^4	0.3	2.5114×10^4	0.6
2.4534×10^4	2.4534×10^4	0.0	2.4603×10^4	0.3	2.4672×10^4	0.6
2.4092×10^4	2.4092×10^4	0.0	2.4161×10^4	0.3	2.4230×10^4	0.6
2.3650×10^4	2.3650×10^4	0.0	2.3719×10^4	0.3	2.3788×10^4	0.6
2.3208×10^4	2.3208×10^4	0.0	2.3277×10^4	0.3	2.3347×10^4	0.6
2.2766×10^4	2.2766×10^4	0.0	2.2836×10^4	0.3	2.2905×10^4	0.6
2.2324×10^4	2.2324×10^4	0.0	2.2394×10^4	0.3	2.2462×10^4	0.6
2.1364×10^4	2.1364×10^4	0.0	2.1478×10^4	0.5	2.1591×10^4	1.1
	Oil Costs					
	1.5 times base case		2 times base case		3 times base case	
base case (million $US/y)	value (million $US/y)	% change	value (million $US/y)	% change	value (million $US/y)	% change
2.6130×10^4	1.6318×10^4	−37.6	6.5053×10^3	−75.1	-1.3119×10^4	−150.2
2.5849×10^4	1.6074×10^4	−37.8	6.2985×10^3	−75.6	-1.3252×10^4	−151.3
2.5418×10^4	1.5645×10^4	−38.5	5.8710×10^3	−76.9	-1.3676×10^4	−153.8
2.4976×10^4	1.5203×10^4	−39.1	5.4290×10^3	−78.3	-1.4118×10^4	−156.5
2.4534×10^4	1.4761×10^4	−39.8	4.9871×10^3	−79.7	-1.4560×10^4	−159.3
2.4092×10^4	1.4319×10^4	−40.6	4.5451×10^3	−81.1	-1.5002×10^4	−162.3
2.3650×10^4	1.3877×10^4	−41.3	4.1032×10^3	−82.7	-1.5444×10^4	−165.3
2.3208×10^4	1.3435×10^4	−42.1	3.6612×10^3	−84.2	-1.5886×10^4	−168.5
2.2766×10^4	1.2993×10^4	−42.9	3.2192×10^3	−85.9	-1.6328×10^4	−171.7
2.2324×10^4	1.2551×10^4	−43.8	2.7773×10^3	−87.6	-1.6770×10^4	−175.1
2.1364×10^4	1.1615×10^4	−45.6	1.8665×10^3	−91.3	-1.7631×10^4	−182.5

objective with respect to the environmental objective is different. Also, the results illustrate that petroleum refineries are more economically attractive than the biorefineries, although the biorefineries can satisfy the fuel demand with a minor environmental impact. Additionally, based on the results, it is possible to conclude that the forest plantations can be important sinks for the CO_2 emissions from the fuel production process, which can be afforded by the refineries. In addition, the three-dimensional Pareto curve is an effective way to present the results since it illustrates the behavior of the different objectives and the decision makers can define the adequate level of the objectives according to their interest.

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It should be noted that the mathematical approach presented in the paper is limited by the number of potential allocations of the different facilities as well as the number of raw materials, products, and processing routes. In this context, the size of the problem depends directly of the number of considered options, which affect the CPU time and the possibility to obtain a feasible solution. For this reason, the number of considered options is limited. This way, one of the main problems is that an important solution could be missed. Finally, some prospects for future work are the extension of the work to a multiperiod model to involve the effect of the time in a more robust way. Additionally, the uncertainty in the demand and price of products could be an interesting contribution for the recent conditions of the market.

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Notes

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NOMENCLATURE

Parameters

CEmis_i^{ref}	unitary cost for the emissions from refineries
$\mathrm{CEmis}_b^{bioref}$	unitary cost for the emissions from biorefineries
Dland_e^{Max}	maximum limit for the available land for afforestation
Dland_e^{Min}	minimum limit for the available land for afforestation
$F_{i2}^{oilMAX1}$	maximum capacity of production for existing refineries
$F_{i2}^{oilMax2}$	maximum capacity of production for new refineries
F_{i2}^{oilMIN}	minimum capacity of production for new refineries
$F_{i2}^{Costref}$	fixed cost to the capital cost of new refineries
$F_{b1}^{biomass\text{-}MAX1}$	maximum processing capacity in the existing biorefineries
$F_{b2}^{biomass\ MIN}$	minimum processing capacity in new biorefineries
$F_{b2}^{biomass\ MAX2}$	maximum processing capacity in new biorefineries
$F_{b2}^{Costbioref}$	fixed cost for the capital cost for new biorefineries
$F_e^{Costeco}$	fixed cost for the capital cost for forest plantations
$F_{o,i2}^{cost\text{-}pip\text{-}oil}$	fixed cost for the capital cost function for the oil transportation to new refineries
$F_{p1,i2,j}^{cost\text{-}pip\text{-}prod\text{-}ref}$	fixed cost for the capital cost function for installing transportation infrastructure
$\mathrm{fl}_{o,i2}^{oil\text{-}MAX}$	maximum limit for the oil transportation to new refineries
$\mathrm{fl}_{o,i2}^{oil\text{-}MIN}$	minimum limit for the oil transportation to new refineries
$\mathrm{f}_{p1,i2,j}^{product\text{-}ref\text{-}MAX}$	maximum transportation limit for products from petroleum to distribution centers
$\mathrm{f}_{p1,i2,j}^{product\text{-}ref\text{-}MIN}$	minimum transportation limit for products from petroleum to distribution centers
$\mathrm{F}_{bm,m,b2}^{cost\text{-}trans\text{-}biomas}$	fixed cost for the capital cost function for transportation infrastructure for biomass to new biorefineries
$\mathrm{fl}_{bm,m,b2}^{biomas\text{-}MAX}$	maximum limit for biomass transportation from harvesting sites
$\mathrm{fl}_{bm,m,b2}^{biomas\text{-}MIN}$	minimum limit for biomass transportation from harvesting sites
$\mathrm{F}_{p2,b2,j}^{cost\text{-}trans\text{-}prod\text{-}bioref}$	fixed cost for the capital cost function for installing transportation infrastructure for products to new biorefineries
$\mathrm{f}_{p2,b2,j}^{product\text{-}bioref\text{-}MAX}$	maximum transportation limit for product to new biorefineries
$\mathrm{f}_{p2,b2,j}^{product\text{-}bioref\text{-}MIN}$	minimum transportation limit for product to new biorefineries
H_Y	operational days
K_F	annualization factor
OC_i^{ref}	operating cost for refineries
$\mathrm{OC}_{bm,b}^{bioref}$	unitary operating cost for biorefineries
$\mathrm{OC}_e^{opecoind}$	unitary operating cost for forest plantations
$\max F_{bm,m}^{biomass\text{-}field}$	availability of biomass in the fields
$\mathrm{UC}_{o,i}^{oil}$	unitary price of oil
$\mathrm{UC}_{p1,i}^{selling\text{-}product\text{-}ref}$	unitary price of products
$\mathrm{UC}_{bm,b,m}^{biomass\text{-}growth}$	unitary cost for biomass production
$\mathrm{UC}_{p2,b}^{revenue\text{-}prod\text{-}bioref}$	unitary price for bioproducts
Uland_e	necessary area for each tree
$\mathrm{UC}_{o,i1}^{pumping\text{-}oil\text{-}exit}$	unitary transportation cost for oil
$\mathrm{UC}_{p1,i1,j}^{trans\text{-}product\text{-}ref}$	unitary transportation cost for products
$\mathrm{UC}_{o,i2}^{pumping\text{-}oil\text{-}new}$	unitary cost for pumping oil to new refineries
$\mathrm{UC}_{p1,i2,j}^{trans\text{-}prod\text{-}ref\text{-}new}$	unitary transportation cost to distribution centers
$\mathrm{UC}_{bm,m,b1}^{trans\text{-}biomass\text{-}exit}$	unitary transportation cost for biomass to biorefineries
$\mathrm{UC}_{p2,b1,j}^{trans\text{-}prod\text{-}bior\text{-}exis}$	unitary transportation cost for bioproducts to distribution centers
$\mathrm{UC}_{bm,m,b2}^{trans\text{-}biomass\text{-}new}$	unitary transportation cost for biomass
$\mathrm{UC}_{p2,b2,j}^{trans\text{-}prod\text{-}bior\text{-}new}$	unitary transportation cost for products to new biorefineries
$V_{i2}^{Costref}$	variable cost to the capital cost of new refineries
$V_{bm,b2}^{Costbioref}$	variable cost for the capital cost for new biorefineries
$V_e^{Costeco}$	variable cost for the capital cost for forest plantations
$V_{o,i2}^{cost\text{-}oil}$	variable cost for the capital cost function for the oil transportation to new refineries
$V_{p1,i2,j}^{cost\text{-}prod\text{-}ref}$	variable cost for the capital cost function for installing transportation infrastructure
$V_{bm,m,b2}^{cost\text{-}trans\text{-}biomass}$	variable cost for the capital cost function for transportation infrastructure for biomass to new biorefineries
$V_{p2,b2,j}^{cost\text{-}trans\text{-}prod\text{-}bioref}$	variable cost for the capital cost function for installing transportation infrastructure for products to new biorefineries
$\alpha_{p2,bm,b}^{product\text{-}bioref}$	conversion parameter for biorefineries
$\alpha_{p1,i}^{product\text{-}ref}$	conversion factor to obtain the refinery production

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$\beta_{o,i}^{CO_2\text{-ext}}$ unitary CO_2 emissions for oil extraction

$\beta_{p1,i}^{CO_2\text{-product-ref}}$ unitary CO_2 emissions for oil refining

$\beta_{p1,i,j}^{CO_2\text{-trans-product-ref}}$ unitary CO_2 emissions for product transportation from refineries

$\beta_{p1,i}^{CO_2\text{-use-product-ref}}$ unitary CO_2 emissions for combustion of products

$\gamma_{bm,b}^{CO_2\text{-biomass-growth}}$ unitary CO_2 emissions for biomass production

$\gamma_{bm,m,b}^{CO_2\text{-biomass-trans}}$ unitary CO_2 emissions for biomass transportation

$\gamma_{b2}^{\text{trans-bior1}}$ capacity exponent for the capital cost function for installing transportation infrastructure for biomass to new biorefineries

$\gamma_{i2}^{\text{trans-ref2}}$ capacity exponent for the capital cost function for installing of transportation infrastructure

$\gamma_{b2}^{\text{trans-bior2}}$ capacity exponent for the capital cost function for installing transportation infrastructure for products to new biorefineries

$\gamma_{i2}^{\text{trans-ref2}}$ capacity exponent for the capital cost function for the oil transportation to new refineries

$\gamma_{e}^{\text{ecoind}}$ capacity exponent for the capital cost function for forest plantation

$\gamma_{b2}^{\text{bioref}}$ capacity exponent for the capital cost function of new biorefineries

γ_{i2}^{ref} capacity exponent for the capital cost function for the new refineries

Variables

C_{i2}^{Capref} capital cost associated with new refineries

C_{i}^{opref} operational cost associated with refineries

$\text{Cost}_{i}^{\text{oil}}$ cost of oil for refineries

$C_{i1}^{\text{trans-oil-exis}}$ $C_{i2}^{\text{trans-oil-new}}$ cost of transportation from wells to new and existing refineries

$C_{i1}^{\text{trans-product-ref-exis}}$ $C_{i2}^{\text{trans-product-ref-exis-new}}$ cost of transportation of products of oil from new and existing refineries to distribution centers

$C_{b2}^{\text{Capbioref}}$ capital cost for new biorefineries

$C_{b}^{\text{op bioref}}$ operation cost for biorefineries

$\text{Cost}_{b}^{\text{biomass-growth}}$ cost for the biomass production

$C_{b1}^{\text{trans-biomass-exis}}$ $C_{b2}^{\text{trans-biomass-new}}$ cost of transportation of biomass from fields to new and existing biorefineries

$C_{b1}^{\text{trans-product-bioref-exis}}$ $C_{b2}^{\text{trans-product-bioref-exis-new}}$ cost of transportation for bioproducts from biorefineries

C_{e}^{opecoind} operating cost for the forest plantations

$C_{e}^{\text{Capecoind}}$ capital cost for installing forest plantations

$C_{e}^{\text{Totalecoind}}$ total cost for forest plantations

$C_{i2}^{\text{Captrans-oil}}$ capital cost for installing transportation infrastructure for petroleum

$C_{i2}^{\text{op trans-oil}}$ operating cost for transportation of petroleum

$C_{i2}^{\text{Captrans-product-ref}}$ capital cost for installing transportation infrastructure for petroliferous

$C_{i2}^{\text{op trans-product-ref}}$ operating cost for the transportation of petroliferous to new refineries

$C_{b2}^{\text{Captrans-biomass}}$ capital cost for the transportation of biomass to new biorefineries

$C_{b2}^{\text{op trans-biomass}}$ operating cost for the transportation of biomass to new biorefineries

$C_{b2}^{\text{Captrans-product-bioref}}$ capital cost for transportation of bioproducts from new biorefineries

$C_{b2}^{\text{optrans-product-bioref}}$ operating cost for transportation of bioproducts from new biorefineries

$\text{Emcap}_{i}^{\text{refinery}}$ emissions captured to refineries

$\text{Em}_{i}^{\text{refinery}}$ total emissions of refineries

$\text{Emcap}_{b}^{\text{biorefinery}}$ captured emissions to biorefineries

$\text{Em}_{b}^{\text{bioref}}$ total emissions from biorefineries

$E_{i}^{\text{oil-ext}}$ emissions from petroleum extraction

$E_{i}^{\text{product-ref}}$ emissions from oil transportation

$E_{i}^{\text{trans-product-ref}}$ emissions from petroliferous transportation

$E_{i}^{\text{use-product-ref}}$ emissions from using products

$E_{b}^{\text{biomass-trans}}$ emissions for biomass transportation

$E_{b}^{\text{bioref-product}}$ emissions for biomass processing

$E_{b}^{\text{trans-prod-bioref}}$ emissions for bioproducts transportation from biorefineries

$E_{b}^{\text{use-prod-bioref}}$ emissions for using bioproducts as biofuels

$\text{Em}_{e}^{\text{ecoind}}$ captured emissions by forest plantations

EOF economic objective function (net profit)

$F_{bm,b}^{\text{biomass}}$ total amount of biomass in biorefineries

$f_{bm,m,b}^{\text{biomass1}}$ Amount of biomass from each field to biorefineries

$F_{bm,m}^{\text{biomass-field}}$ total amount of distributed biomass from biomass fields to biorefineries

$F_{p2,b}^{\text{product-bioref}}$ flow of bioproducts in biorefineries

$f_{p2,b,j}^{\text{product-bioref1}}$ flow of bioproducts sent to distribution centers

F_{i}^{oil} total flow of petroleum in refineries

$f_{o,i}^{\text{oil1}}$ flow of petroleum distributed from producer regions to refineries

$F_{p1,i}^{\text{product-ref}}$ total flow of products in refineries

$f_{p1,i,j}^{\text{product-ref1}}$ flow of product distributed from refineries to distribution centers

$\text{Jobs}^{\text{refinery}}$ new generated jobs by refineries

$\text{Jobs}^{\text{bioref}}$ new generated jobs by biorefineries

$\text{Jobs}^{\text{ecoind}}$ new generated jobs by forest plantations

N_{Te} total number of trees per forest plantation

$\text{NE}_{b}^{\text{biomass-growth}}$ net captured emissions during the biomass production

NetEmission environmental objective function (net emissions)

$\text{Profit}^{\text{refinery}}$ total profit of refineries

$\text{Profit}^{\text{ecoind}}$ annual profit for forest plantations

$\text{Revenue}_{i}^{\text{sold-product-ref}}$ revenue for selling products of refineries

$\text{Revenue}_{b}^{\text{sold-prod-bioref}}$ revenue for selling bioproducts

TOTALJOBS social objective function (total generated jobs)

Binary Variables

y_{i2}^{ref} binary variable to define if a new refinery is installed

y_{b2}^{bioref} binary variable to define if a new biorefinery is installed

y_{e}^{ecoind} binary variable to define if a forest plantation is installed

$y_{o,i2}^{\text{pip-oil-ref}}$ binary variable to define if there is transportation of oil from well oil to refineries

$y_{p1,i2,j}^{\text{pip-product-ref}}$ binary variable to define if there is transportation of petroliferous to distribution centers

$y_{bm,m,b2}^{\text{trans-biomass}}$ binary variable to define if there is transportation of biomass to new biorefineries

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$y_{p2,lo,j}^{trans-prod-biocel}$ binary variable to define if there is transportation of bioproducts to distribution centers

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Research Article

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A Multistakeholder Approach for the Optimal Planning of Sustainable Energy Systems

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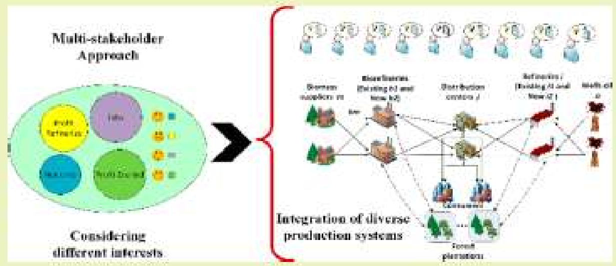
Supporting Information



ABSTRACT: This paper presents a mathematical programming model for the optimal planning of an integrated system for producing fuels and biofuels considering the interaction with facilities capable of capturing emissions from biorefineries and refineries and receiving a monetary benefit; these facilities can be named eco-industries or forest plantations. The proposed approach is formulated as a multistakeholder scheme to consider the benefits and effects in each one of the involved supply chain entities and to determine how the interactions between the different stakeholders take place. The proposed approach takes into account the profit of biorefineries, refineries, and forest plantations as well as the emissions and jobs generated in each one of the involved entities. Additionally, it considers local and imported raw materials to satisfy the energy demand. Also, the approach considers features such as the project lifetime; the availability of resources; the amount and type of products that should be produced; and the allocation and capacity of the refineries, biorefineries, and forest plantations. The mathematical approach was applied to a nationwide case study for Mexico, considering the creation of new jobs, overall emissions, and net profit as main objectives.

KEYWORDS: *Supply chains, Energy systems, Multistakeholder, Optimal planning, Carbon capture*

INTRODUCTION

According to the Worldwide Economic Forum, fossil energy consumption continues to increase but at slower pace during the past decade because of the increasing use of renewable energy; even so, the continuous increase of energy demand in the world is boosted by population and economic growth. The phenomena of increasing energy demand and population growth are intimately related with climate change. The global warming associated with climate change is a serious environmental problem, and it is producing alarming impacts on the environment and humans, mainly due to generation of large amounts of greenhouse gas emissions mostly resulting from the burning of fossil fuels. This is not an easy problem to solve; however, many efforts have been implemented, for example the use of renewable energy or the use of biomass to produce biofuels. In this context, Lundgren et al.[1] stated that it is necessary to limit greenhouse gas emissions from human activities. Yu and Zhu[2] explained how to limit carbon emissions in different countries and international competition for new energy sources, because energy is fundamental to the prosperity and security of nations. Several alternatives have been proposed to address this problem. Carbon tax policy has become an effective way to establish limits of carbon emissions in many countries, because carbon emissions mean additional costs for industries and thus have an impact on profits.[3] Kober et al.[4] investigated the macroeconomic consequences of mitigating greenhouse gas emissions in Latin America. Vandyck et al.[5] presented a model, based on the Paris Agreement, to assess the mitigation policies limiting global warming to 2 °C above preindustrial levels. Currently, sustainability and economic growth limit the agenda of international policy discussions. This is mainly because there is a growing concern about climate change, and at the same time countries seek economic growth. In terms of climate change, the concern is that assuming that human activity continues as it is, the global warming could potentially have adverse impacts on the environment and the global economy.[6]

To address this problem, other authors have proposed alternatives involving renewable energy sources. For example, Hong et al.[7] mentioned that the use of biofuels is a sustainable way to satisfy energy needs. Also, Ng et al.[8] stated that biomass is a potential renewable energy source for producing biofuels,

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chemicals, and other value-added products using several processing technologies. In recent years, the biogas production capacity has been greatly enlarged in Germany. For instance, Guenther-Lübbers et al.[9] implemented a study to provide information about the positive effects of biogas production on the socio-economic aspects of rural areas. Moreover, CO_2 utilization is gaining attention as a greenhouse gas abatement strategy complementary to CO_2 storage.[10] Also, Tapia and Tan[11] stated that carbon capture and storage is an important way to reduce industrial emissions. Additionally, Brunori et al.[12] studied an oak plantation as part of an activity focus on ecosystem restoration of an area where lignite has been extracted since 1863. They calculated the carbon sequestered by the oak plantation biomass, during the whole life span, and measured through the life cycle assessment the environmental impact in terms of global warming; they demonstrated that the tree plantation can be an important carbon dioxide sink especially if the selected species have a long-lasting growth level and low impact activities in plantation management.

Other authors have proposed the use of mathematical programing as an alternative tool for designing integrated schemes for a better use of energy, designing different types of supply chains, and proposing optimization methodologies. For example, Grossmann[13] provided a review of mixed-integer nonlinear and disjunctive programming techniques, which are powerful tools to solve diverse optimization problems; this is important because most of the supply chain planning problems and process systems engineering problems use some of these techniques in their solution. For instance, You and Grossmann[14] proposed a mathematical formulation for inventory management in supply chain design; they considered the minimization of weighted cost for transportation, installation of facilities, and inventory costs. Also, Hugo and Pistikopoulos[15] presented a methodology based on mathematical programing including life cycle assessment for designing and planning supply chain networks using multiobjective optimization. In addition, Guillén-Gosálbez and Grossmann[16] addressed the design of sustainable chemical supply chains applying uncertainty in the life cycle inventory linked to the supply chain operation.

Furthermore, Sánchez-Bautista et al.[17] proposed a mathematical programming approach for the optimal design of the topology of a supply chain for the production of fuels through refineries and biorefineries, integrated with forest plantations focused on decreasing the total greenhouse gas emissions, while simultaneously maximizing the net profit of the system and generation of jobs; the results are shown through a Pareto curve. However, in that work the three objective functions are analyzed only globally; it is necessary to implement a deeper analysis of their individual effect for multiple decision-makers, because it shows just a set of possible solutions through a three-dimensional Pareto curve.

The development of macro-economic energy projects has a set of inherent interest conflicts. First, the investors want to ensure the best economic performance of the system. On the other hand, politic entities are interested in the social and ecological impact of new facilities, as well as the economic performance. Finally, the local communities consider the environmental impact and social benefits of implementing technological projects.[18] The traditional multiobjective approaches consider and limit the problem to explore the Pareto front and present the different optimal solutions. The designer needs to define, according to the particular criteria, a compromise solution between different objectives.[19] However, the presence of multiple participants with different objectives, preferences, and criteria leads to conflicts, which can affect the development or operation of new projects.[20] The main problem is defining a multicriteria decision-making framework that allows the negotiation between the participants, reducing the info-gap and creating a bargain environment for dialoguing and reaching a compromise solution.[21]

Therefore, the multistakeholder framework needs to include, in addition to the optimal solutions, the effects of using the particular criteria of the participants in the decision-making process. In this way, each of the stakeholders can be conscious of the consequences of using its criteria in the final configuration of the system and the inherent effects of the solutions proposed by other stakeholders. According to Zavala,[22] the generation of a Pareto curve has two important drawbacks. The first one is that the final decision is taken by a single decision-maker, while almost any task involves multiple decision-makers. The second one is that the complexity of developing a Pareto front is exponential with respect to the number of objectives. Furthermore, Dowling et al.[23] confirmed that several multi-objective optimization approaches have difficulty quantifying how satisfied the involved stakeholders are with a given decision and how representative the stakeholder opinions are of those of the entire population. For that reason, Dowling et al.[23] presented a methodology to address the priorities of multiple stakeholders and multiple objectives without the computation of the full Pareto set.

An interesting analysis was made by Marre et al.,[24] where they addressed whether the economic valuation of ecosystem services (ESV) is useful to decision-makers; this analysis revealed the existence of a gap between the theory and practice of the ESV use. In theory, ESV is presented and perceived as a useful tool, but in practice, ESV appears to be rarely used, and it has a weak influence on policy. This study is important because it shows the usefulness of this type of analysis for decision-makers.

To include an emission reduction strategy and a sustainable introduction of biofuels production, this work presents an approach for producing biofuels and fossil fuels via biorefineries and oil-refineries aiming to reduce greenhouse gas emissions associated with the production of fuels with integration of forest plantations to capture the generated CO_2 emissions. It is important to emphasize that this paper avoids the disadvantages of a generator multiobjective method like a Pareto curve through a multistakeholder approach taking into account the individual profit for each entity, the generated emissions, and the generated jobs for each entity as a social objective.

Furthermore, it should be noted that several works have studied multistakeholder problems previously (see Fuentes-Cortes et al.[25] and González-Bravo et al.[26]). On the one hand, Fuentes-Cortes et al.[25] determined that the carbon and water prices must be increased by 2 or 3 orders of magnitude to provide an economically attractive income. Additionally, Fuentes-Cortes et al.[25] applied their methodology to a system for planning water and energy use; however, the system topology was previously defined. On the other hand, González-Bravo et al.[26] applied a multistakeholder methodology for designing power and water distribution networks. The model by González-Bravo et al.[26] is capable of obtaining the location and size of the involved entities in water networks. It should be noted that the objectives in that methodology are considered in anoverall way (one objective for jobs, one objective for emissions, and one objective for profit).

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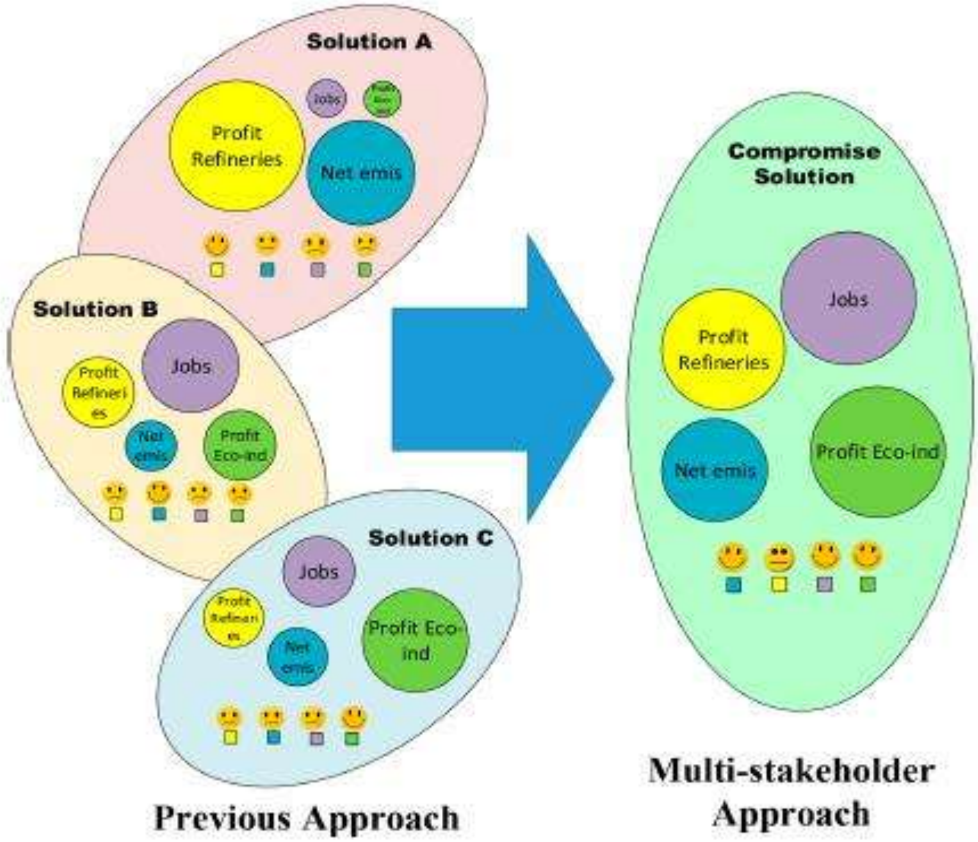

Figure 1. Overview of the contribution for the addressed problem.

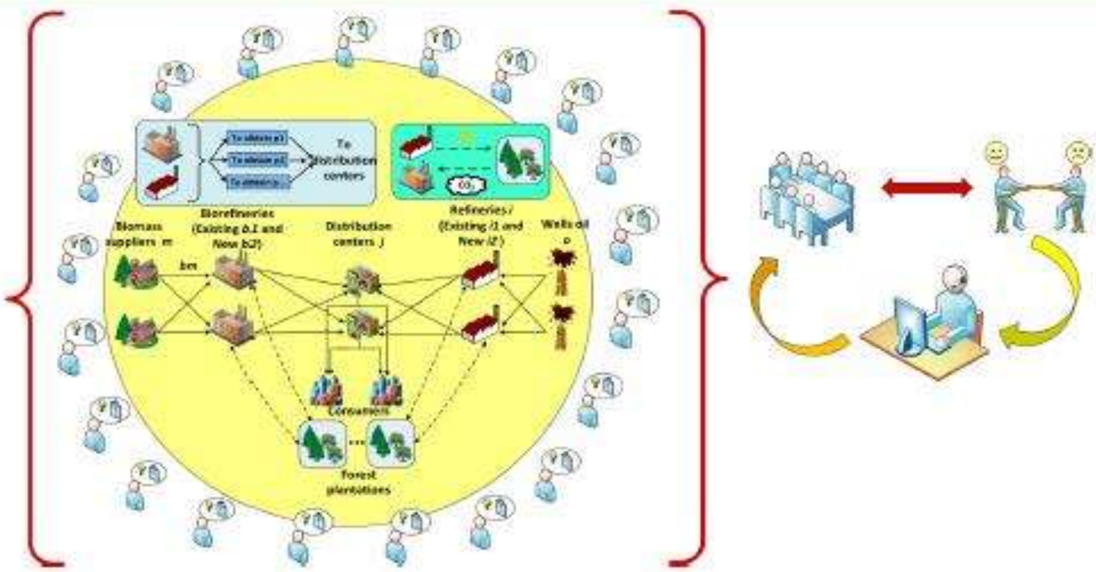

Figure 2. Proposed superstructure for an integration problem of refineries, biorefineries, and forest plantations considering a multistakeholder scheme.

However, multistakeholder approaches have not been applied to supply chains directly based on biomass, because most of the previously reported methodologies have used multiobjective approaches considering only 1−3 objectives. In this respect, the proposed approach takes into account different objectives for each one of the considered systems in the system (biorefineries, refineries, and forest plantations). It is worth noting that the supply chain configuration of one supply chain affects directly the involved objectives. For example, if the amount of forest plantations increases, then the emissions decrease and the profits for refineries and biorefineries decrease. Moreover, an important difference with previous works is that this paper proposes a mathematical programming model without a predefined topology because the interconnection between nodes of all considered supply chains (fuel production, biofuel production, and eco-industries) is obtained when the optimization problem is solved. Additionally, the proposed scheme takes into account the interaction of diverse production systems such as biofuel production, fossil fuel production, and afforestation. Also, each of the considered systems is associated with different sustainability dimensions, such as jobs for forest plantations, jobs for refineries, profit for biorefineries, profit for refineries, and CO_2 emissions.

Figure 1 shows an overview of the addressed problem and presents the focus of the proposed approach, which is looking for better solutions for all the involved parts and not just one good overall solution that may not be good enough for some involved participants.

■ PROBLEM STATEMENT

The proposed approach is a mathematical programming formulation for the optimal planning and integration of a fuel production system considering forest plantations for CO_2 capture under a multistakeholder scheme. It is worth noting that a multistakeholder scheme implies multiple decision-makers or multiple interested parts; it requires new perspectives and principles to determine compromises of all participants, and the compromise must give precedence to a consensus and win–win results. The problem can be defined based on the superstructure represented in Figure 2, and this is stated as follows:

Given:

- Data of potential locations for:
  - Biomass suppliers
  - Forest plantations
  - Biorefineries
  - Refineries
- Costs associated with installing and operating the proposed system.

Then, the problem consists of determining the following:

- The size and location of the facilities (biomass suppliers, oil wells, refineries, biorefineries, and forest plantations)
- The interconnection between them
- The amount of consumed raw material (biomass and oil)
- The jobs generated by the integrated supply chain

Furthermore, the proposed model incorporates pollution-trading concepts to reduce emissions through a set of forest plantations with different capacities and sizes. It should be noted that the fuel demand, which can be satisfied via fossil fuels or biofuels, is received from several distribution centers. Finally, the model is solved through a multistakeholder approach, which involves solving the problem for the maximization of a set of weighted objective functions associated with different priorities for each stakeholder.

■ MODEL FORMULATION

The mathematical model considers integration between biorefinery and refinery production with forest plantations (known as eco-industries) in order to obtain overall emissions, jobs, and profit for each one of the considered facilities. The mathematical approach consists of mass balances between the different entities of the supply chain; technical and economic constraints; and functions to evaluate the performance of the system such as net annual profit, generated jobs, and net emissions, which are described in the electronic Supporting Information. The model formulation was improved to include a weighted function to take into account the different significances for each one of the involved stakeholders, which is shown in eq 1. This function converts the original multiobjective problem into a single-objective optimization model, where the objective function is a compensated function known as the compromise solution. Equation 1 establishes that the compromise function is equal to the sum of a significance weight multiplied by a normalized function for each one of the objective functions.

$$\begin{aligned} CS_i = {} & w_i^{PR}\cdot\frac{P^R - P^{L\text{-}R}}{P^{U\text{-}R} - P^{L\text{-}R}} + w_i^{PB}\cdot\frac{P^B - P^{L\text{-}B}}{P^{U\text{-}B} - P^{L\text{-}B}} \\ & + w_i^{PF}\cdot\frac{P^F - P^{L\text{-}F}}{P^{U\text{-}F} - P^{L\text{-}F}} + w_i^{ET}\cdot\frac{E^{U\text{-}T} - E^T}{E^{U\text{-}T} - E^{L\text{-}T}} + w_i^{JR}\cdot\frac{J^R - J^{L\text{-}R}}{J^{U\text{-}R} - J^{L\text{-}R}} \\ & + w_i^{JB}\cdot\frac{J^B - J^{L\text{-}B}}{J^{U\text{-}B} - J^{L\text{-}B}} + w_i^{JF}\cdot\frac{J^F - J^{L\text{-}F}}{J^{U\text{-}F} - J^{L\text{-}F}}, \ \forall\ i \in I \end{aligned} \tag{1}$$

It should be noted that the weights (w_i^{PR}, w_i^{PB}, w_i^{PF}, w_i^{ET}, w_i^{JR}, w_i^{JB}, and w_i^{JF}) represent the importance factors for each one of the interest functions, which are the profit of refineries (P^R), profit of biorefineries (P^B), profit of forest plantations (P^F), net emissions (E^T), generated jobs by refineries (J^R), generated jobs by biorefineries (J^B), and generated jobs by forest plantations (J^F), respectively. They represent the level of preference of each stakeholder about the objective functions according to the individual criteria ($0 \le w \le 1$). In this way, this formulation allows each stakeholder to define their priorities about the performance of the system. The parameters with the superscripts U and L are the upper and lower bounds for the functions, respectively. These parameters are obtained via the maximization and minimization of the individual functions without accounting for others. In addition, these parameters define the utopia (UP) and nadir (NP) points

The multistakeholder scheme is based on the maximization of the compromise solution (CS_i) for all stakeholders (i). This stage produces an optimal solution for each decision-maker but suboptimal solutions for all others. Additionally, it is possible to obtain a general compromise solution. For this case, the compromise solution is equal to the average of all individual optimal compromise solutions of each decision-maker. This is obtained by minimizing the absolute value of the difference between the desired solution of each stakeholder and the compromise solution to be found. This is shown in eq 2.

$$\min\left\{ABS\left[CS^* - (1/I)\cdot\sum_i CS_i\right]\right\} \tag{2}$$

It should be noted that eq 2 is a noncontinuous function; therefore, this function was discretized in two cases. The first case is when the difference between the desired compromise solution is negative, and the second case is when that difference is positive. The associated disjunction is represented as follows:

$$\begin{bmatrix} Y1 \\ CS^* \ge (1/I)\sum_i CS_i \\ ABS = CS^* - (1/I)\sum_i CS_i \end{bmatrix} \vee \begin{bmatrix} Y2 \\ CS^* \le (1/I)\sum_i CS_i \\ ABS = (1/I)\sum_i CS_i - CS^* \end{bmatrix}$$

Previous disjunction is reformulated via the convex hull methodology. In this respect, only one binary variable can be activated; therefore, the sum of binary variables should be equal to one.

$$y1 + y2 = 1 \tag{3}$$

In addition, each continuous variable in previous disjunction should be expressed as a function of disaggregated variables:

$$ABS = abs1 + abs2 \tag{4}$$

$$CS^* = CS1^* + CS2^* \tag{5}$$

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Table 1. Summary for the Compromise Solution and Dissatisfaction Factor for Each Case

case	w_i^{PR}	w_i^{PB}	w_i^{PF}	w_i^{ET}	w_i^{JR}	w_i^{JB}	w_i^{JF}	CS_i	DR
1	1	0	0	0	0	0	0	0.99	0.70
2	0	1	0	0	0	0	0	1.00	0.69
3	0	0	1	0	0	0	0	1.00	0.69
4	0	0	0	1	0	0	0	1.00	0.69
5	0	0	0	0	1	0	0	1.00	0.69
6	0	0	0	0	0	1	0	1.00	0.69
7	0	0	0	0	0	0	1	1.00	0.69
8	1/7	1/7	1/7	1/7	1/7	1/7	1/7	0.78	1.17
9	1/2	0	0	0	1/2	0	0	0.99	0.70
10	0	1/2	0	0	0	1/2	0	0.66	1.55
11	0	0	1/2	0	0	0	1/2	1.00	0.69
12	1/3	0	0	1/3	1/3	0	0	0.87	0.94
13	0	1/3	0	1/3	0	1/3	0	0.76	1.21
14	0	0	1/3	1/3	0	0	1/3	0.24	6.10
15	1/4	1/4	0	0	1/4	1/4	0	0.82	1.06
16	1/4	0	1/4	0	1/4	0	1/4	0.79	1.14
17	0	1/4	1/4	0	0	1/4	1/4	0.83	1.03
18	1/5	1/5	0	1/5	1/5	1/5	0	0.79	1.14
19	1/5	0	1/5	1/5	1/5	0	1/5	0.54	2.11
20	0	1/5	1/5	1/5	0	1/5	1/5	0.86	0.96

Also, the disaggregated variables are established according to each part of the disjunction and limited by the binary variables:

$$abs1 = CS1^* - (1/I)\cdot y1\cdot \sum_i CS_i \quad (6)$$

$$abs2 = (1/I)\cdot y2\cdot \sum_i CS_i - CS2^* \quad (7)$$

Furthermore, eqs 5 and 6 are used to activate binary variables because the binary variable $y1$ is equal to 1 when $CS1^*$ is greater than the average compromise function, while the binary variable $y2$ is equal to 1 when $CS2^*$ is lower than the average compromise function.

$$CS1^* \geq (1/I)\cdot y1\cdot \sum_i CS_i \quad (8)$$

$$CS2^* \leq (1/I)\cdot y2\cdot \sum_i CS_i \quad (9)$$

Finally, the disaggregated variables are limited to ensure that if the binary variable is activated, then the disaggregated variables are equal to zero and thus their contribution to the corresponding total variable is equal to zero.

$$CS1^* \leq CS^{max}\cdot y1 \quad (10)$$

As can be seen, the discontinuous function (absolute value) is transformed into a mixed integer linear programming (MILP) optimization problem, which can be solved through any optimization solvers, such as CPLEX.

In addition, the dissatisfaction for each stakeholder can be calculated, which is related to the difference between the final compromise solution and the compromise solution for each stakeholder.

$$\text{Dissatisfaction-relation}_i = DR = ABS\left(\frac{CS^* - CS_i}{CS_i}\right),\ \forall i \in I \quad (11)$$

Finally, in order to analyze the economic, environmental, and social behavior, the individual objective functions are concentrated in main objective functions, which are the net emissions, total profit, and total generated jobs. These grouped functions are useful to represent the system in a general way. The total profit and total jobs are stated as follows:

$$\text{Total profit} = TP = P^R + P^B + P^F \quad (12)$$

$$\text{Total jobs} = TJ = J^R + J^B + J^F \quad (13)$$

Proposed Approach for the Solution of the Multiobjective Optimization Problem by a Multistakeholder Approach. The solution of the multiobjective optimization problem considers conflicting criteria. Hence, the multistakeholder decision-making approach tries to identify ideal and worst solutions and the associated trade-offs for the system, seeking to make a final decision that reaches a form of consensus or compromise solution (see Fuentes-Cortes et al.[27]).

To solve the multiobjective optimization problem applying the multistakeholder approach, first there are established the considered objective functions: profit for refineries, biorefineries, and forest plantations; overall net emissions; and generated jobs for refineries, biorefineries, and forest plantations. Then, it is needed to maximize and/or minimize each objective function to determine the lower and upper bounds for each one of objective functions; these solutions define the coordinates of the utopia and nadir points.

The solution of the utopia point is obtained through the "best solution" for each objective (maximum value for profits and jobs whereas minimum value for overall net emissions). The utopia point cannot be implemented, as the objectives are conflicting, but it is used as an ideal reference. The nadir solution (NS) is obtained through the worst-case values for the objectives at the utopia point. For example, when maximizing refineries' profit and jobs individually, the worst-case value for emissions is obtained. This implicitly shows the trade-off between objectives (see Fuentes-Cortes et al.[27]). Then, there are established weights to reflect priorities by different decision-makers to calculate compromise solutions for each stakeholder. Finally, there is obtained a global compromise solution and dissatisfaction relation of stakeholders.

■ CASE STUDY

The proposed mathematical approach was applied to a case study for Mexico; six existing refineries in Mexico and three potential locations for installing additional refineries were considered, based on the demand for products and the existing infrastructure to transport raw materials and products. Regarding biorefineries, the possibility of installing six biorefineries was considered, because currently there are no biorefineries in this country. One eco-industry (i.e., forest

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Table 2. Values for the Concentrated Objective Function for Each Case

case	1	2	3	4	5	6	7	8	9	10
TP ($\times10^{-10}$)	2.78	2.56	2.03	2.13	2.28	2.53	2.03	2.16	2.71	2.69
E^T ($\times10^{-10}$)	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73
TJ ($\times10^6$)	0.03	0.03	3.08	3.08	0.04	0.04	3.08	3.09	0.04	0.03
case	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
TP ($\times10^{-10}$)	2.03	2.64	2.16	2.66	2.67	2.16	1.69	2.67	2.67	2.16
E^T ($\times10^{-10}$)	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73	1.73
TJ ($\times10^6$)	3.08	0.04	3.07	0.03	0.05	3.08	3.09	0.05	0.04	3.09

plantation) for each Mexican state was considered; however, these are limited by land availability as well as climatic conditions.

Concerning the raw materials for biorefineries, different biomass types were considered, including sugar cane, sweet sorghum, woodchip, African palm, jatropha, and agave waste. Also, the case study considers one biomass supplier for each state of the country; nevertheless, each biomass supplier contains different biomass availability according to data from SAGARPA.[24] Furthermore, according to PEMEX (The Mexican Company of Petroleum), oil wells as places to extract petroleum were taken into account, which are denoted "Territorial waters", "Tabasco", "Veracruz", "Chiapas", "Puebla", "Tamaulipas", and "San Luis Potosi". In addition, 45 distribution centers corresponding to storage and distribution terminals of PEMEX allocated around the Mexican territory were considered.

It is worth noting that the proposed mathematical formulation is general, and it can be applied to other case studies considering the specific data. The required parameters are listed in the nomenclature section as "Noncomputed Parameters", while the parameters computed through the optimization problem (to obtain boundaries for other variables) can be obtained from solving the problem for the different involved objectives. The needed data for the case study are presented in the Supporting Information.

RESULTS

The optimization model is a multiobjective mixed-integer linear programming problem. The model consists of 6407 continuous variables, 2161 binary variables, and 5431 constraints. It was coded in the GAMS software. This model was solved using the solver CPLEX with a computer with an Intel Core i7 processor at 2.90 GHz with 16 GB of RAM. The average CPU time for each solution of the mathematical model was around 0.156 s.

The multistakeholder approach considered 20 individual stakeholders, which are associated with diverse weighting factors. The used weights represent the preferences and criteria of the participants. As can be seen, the complexity of the problem increases as more participants with different criteria and priorities are added to the multicriteria decision-making environment. We have presented a set of representative criteria for the problem avoiding the inclusion of stakeholders who can use similar levels of preference. Obviously, the used formulation allows including stakeholders with the same level of priorities about the objective functions. Table 1 summarizes the value of the weighting factors, the compromise solutions for each one, and the dissatisfaction ratio for each case. Table 2 presents the values of the concentrated objective functions. It is important to note that the dissatisfaction value is obtained for each of the stakeholders with respect to the compromise solution, which is the solution without considering weights in the objective functions.

According to Tables 1 and 2, the case with the highest dissatisfaction ratio is case 14. The dissatisfaction ratio for this case is 6.10, where the associated objectives to biorefineries and refineries (profit and jobs) are neglected. It means that the objectives related with forest plantations have higher weights. Also, it can be noted that the total jobs is one of the lowest values for the remaining solutions. Moreover, there are several cases with low dissatisfaction ratios; one of these is case 11, whose objectives related to forest plantations are weighted. In case 11, the number of jobs is improved significantly to 3.08 million new jobs, while the profit is reduced from \$US 2.66 $\times$ 10[10] to \$US 2.03 $\times$ 10[10] with respect to case 14.

Figure 3 shows diverse points, where the total profit and generated jobs are maximized, whereas the emissions are

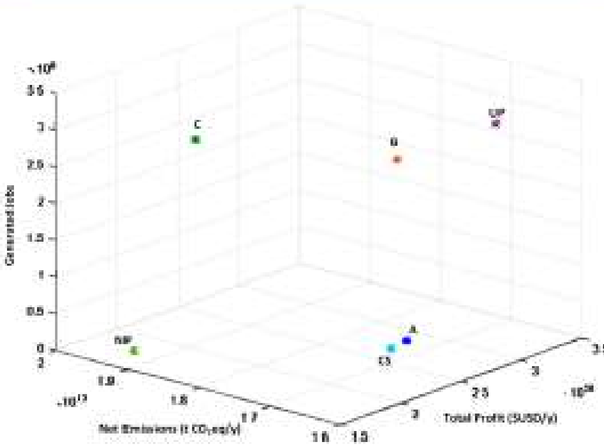

Figure 3. Representation of diverse solutions for the proposed approach: best profit value (A), best jobs value (B), best total emissions value (C), utopic solution (UP), nadir solution (NP), and compromise solution (CS).

minimized; this figure also shows the points for the utopian solution, the nadir solution, and the compromise solution. Point A does not consider the environmental and social objectives; it represents the solution of maximum profit, and this point could be a feasible point. However, the targets for emissions and number of jobs are far from their best values. In addition, this point is the closest point to the compromise solution, but it moves away from the utopia solution with respect to the number of jobs. Point B does not consider the economic and social objectives; it represents the solution with the lowest emissions. Point C is given by the solution of maximum number of jobs without considering the other objectives. The utopia point denotes the best solution, although this solution is infeasible,

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and it is already represented by the maximum total profit, the maximum number of jobs, and the minimum emissions; therefore, this solution is not possible to implement.

Table 3 shows numerical results of points detailed in Figure 3. It is important to note that the utopia point and compromise solution are compared with solutions A, B, and C. For instance, comparing point A with the utopia point, it can be noted that the total profit in point A is 7.3% lower than the total profit in the utopia point, and the net emissions are 5.51% lower than the net emissions in UP; the total jobs are 98.77% lower than the jobs of the UP. It can be seen that comparing point B with respect to the utopia point for the emissions, there is not any difference. These are the same in both cases, because in point B emissions are minimized and in the utopia point emissions are also minimized.

Table 3. Results for Compromise Solution, Utopic Point, and Solutions A, B, and C and Comparison between Points A, B, and C with Utopic and Compromise Solutions

point	total profit (US MM)	net emissions (tonne × 10^6)	total jobs
A	28 120	173.20	38 030
B	22 030	164.10	3 085 800
C	17 630	185.10	3 087 000
UP	30 335	164.14	3 086 981
NP	17 197	193.05	32 823
CS	26 581	172.63	29 804
% DIF A-UP	7.30	5.51	98.77
% DIF B-UP	27.37	0	0.04
% DIF C-UP	41.88	12.76	0
%DIF A-CS	−5.79	0.33	−27.59
%DIF B-CS	17.12	−4.94	−10 253.30
%DIF C-CS	33.68	7.22	−10 257.32

Moreover, there is not difference between point C and UP concerning the total jobs.

To compare points A, B, and C with respect to the compromise solution, it is necessary to clarify that the negative sign (−) indicates the direction with respect to CS; for example, the total profit in point A is 5.78% larger than in CS, this means that the profit in CS is below profit in A.

Figure 4 shows the results for different important points such as the compromise solution for each weighted case, utopic and nadir solutions (lower and upper bounds), and global compromise solution. It is important to emphasize that most of the points are far, at least in one objective, from the utopia point.

This way, UP is the utopic point; this is an infeasible point because this point represents the best possible values for all objectives, which is not possible in a real system because the considered objectives are in opposition. Hence, large differences between UP and other points such A, B, C, or CS are expected.

Point B is obtained by minimizing net emissions; therefore, point B represents the point with the lowest emissions level; for that reason, the number of forest plantations is maximized. In this regard, the number of jobs is increased because forest plantations have the biggest unitary factor for jobs by comparison with biorefineries and refineries. In addition, point C represents the maximum number of jobs, which corresponds to the point with the most number of forest plantations.

Finally, it is important to remember that point CS is not the point where jobs, net profit, and emissions are optimized. Point CS is the point where most of the optimal solutions for each stakeholder are obtained. Each one of the stakeholders has different priorities. For example, for some of them, jobs are not important (see Table 1). Furthermore, Figure 3 indicates that many solutions of the weighted cases are close to the global

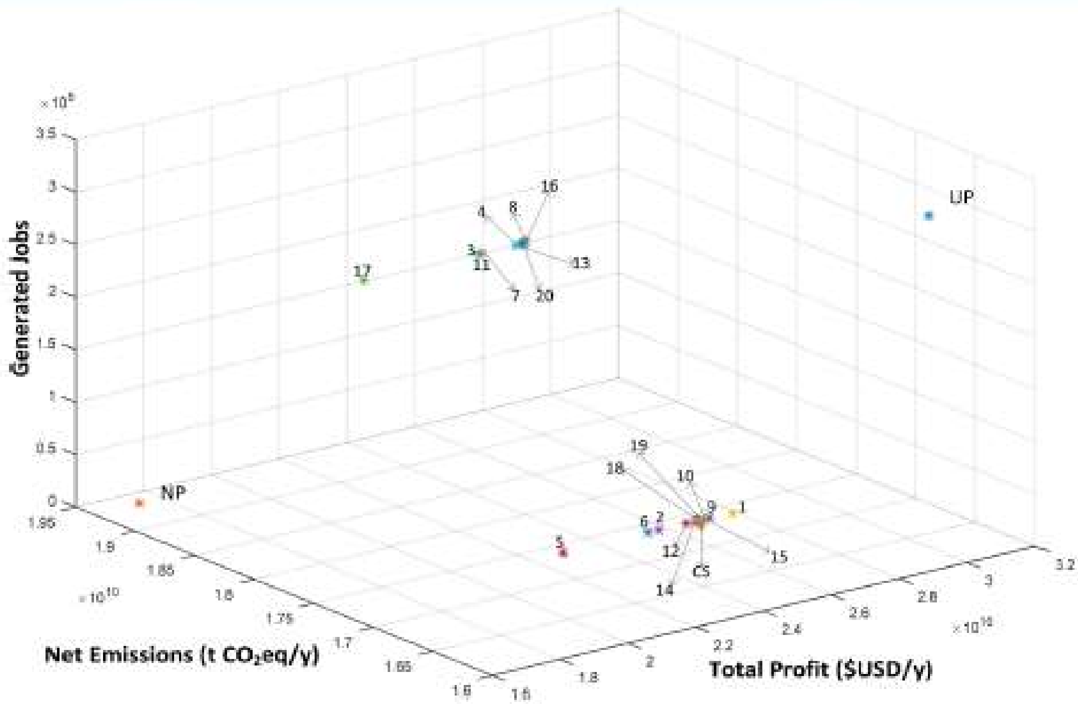

Figure 4. Solutions for the multistakeholder approach considering different cases.

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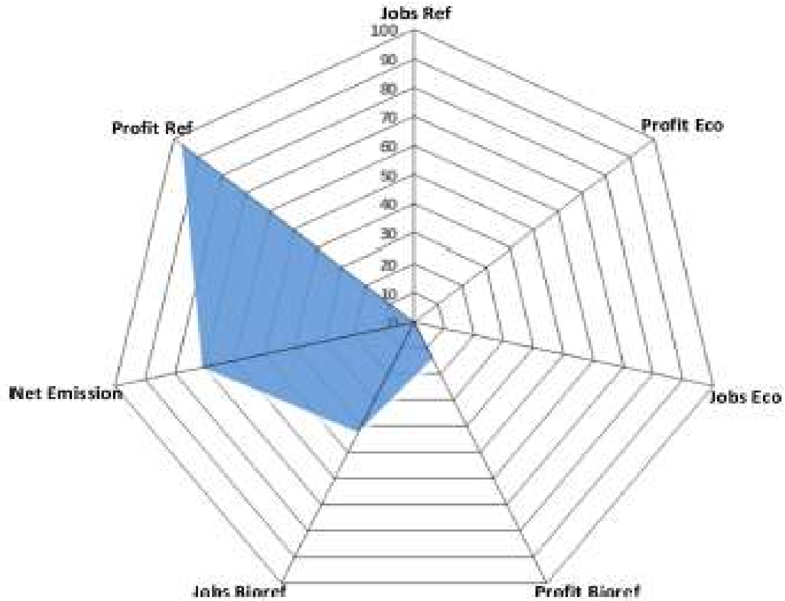

Figure 5. Satisfied ideality proportion for each objective function with respect to the compromise solution.

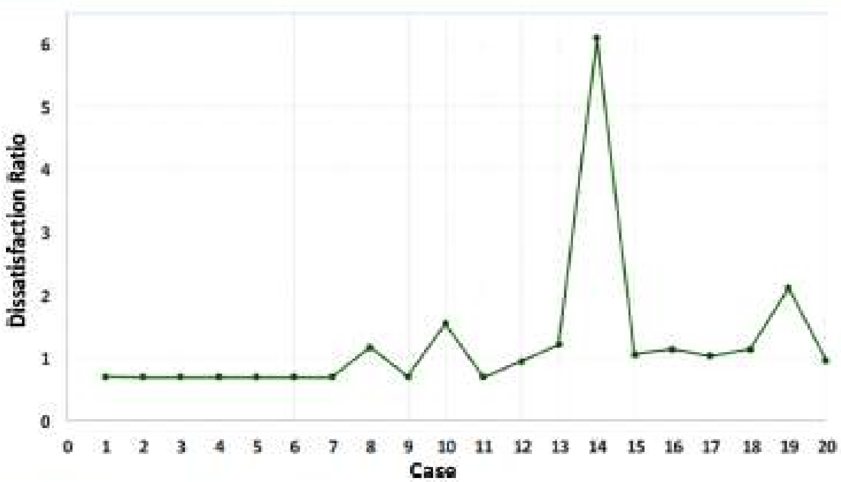

Figure 6. Dissatisfaction proportion for each stakeholder case.

compromise solution, which can give an overview of the individual optimal solution behaviors.

In addition, Figure 4 shows that 11 optimal solutions are close to the CS point, while only 1 solution is close to C point, and the remaining solutions have levels of jobs similar to that of point C but different values for profit and emissions.

Figure 5 shows the trade-offs and behaviors of the objective functions in the compromise solution set. First, it should be understood that 100 means that the function is close to its ideal value, while 0 means that its value is far from this amount; it does not mean that the function value is 100 or zero. Hence, it is observed that the solution tries to compensate all objectives; for instance, it tries to achieve the maximum profit of refineries because the revenue of these is higher than biorefineries and forest plantations. Also, if biorefineries are economically nonviable processes, the solution tries to reduce biorefinery losses, because they represent a process that is environmentally friendly because it contributes to decreasing emissions. Also, it can be seen from Figure 5 that the objective functions for forest plantations are completely distant from their ideal value; it is because their implementation promotes the reduction of the refineries' profit because of the charge for emitted carbon.

In addition, it can be observed that the compromise solution meets at least the economic objective (i.e., profit of refineries) and the environmental and social objectives (i.e., generated jobs in biorefineries).

In Figure 6 it is important to note that the dissatisfaction is related to weights of importance given for each case. For example, case 14 shows the highest dissatisfaction proportion. This is because in that case, the objectives of forest plantations as profit and jobs in eco-industries and total emissions are weighted; consequently, the objectives related to eco-industries are not really satisfied (Figure 5). In addition, it is worth noting that the most important contribution from using this method-

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ology consists of reaching a trade-off for all the participants so they are pleased and providing a discussion framework for negotiating an optimal solution which can satisfy the criteria of most of the decision-makers.

On the one hand, it is important to note that the present approach is able to generate optimal solutions for each one of the stakeholders (see Figure 4). These optimal solutions are obtained for multiple stakeholders associated with their own priority scenario (see Table 1); each scenario denotes one stakeholder with different priorities. Subsequently, the reported solution (CS*) is the closest solution to the average for optimal solutions for each stakeholder. It should be noted that some stakeholders might be unsatisfied or disagree with the reported solution; however, the proposed methodology tries to decrease their dissatisfaction.

On the other hand, the reported methodology has considered that each stakeholder has the same weight for the decision-making process (to do not give preference). Nevertheless, it is flexible, and the priorities can be changed (different weight factors in eq 1) depending on the specific case study or if the reported solution does not satisfy most of the stakeholders.

CONCLUSIONS

This work has presented a model formulation for the planning and integration of the fuel production system integrated with forest plantations applying a solution approach based on a multistakeholder scheme. The model incorporates the specific economic objectives for the stakeholders involved as well as the created jobs and overall emissions as individual objectives. A multistakeholder optimization approach is presented to compensate the considered objectives and to obtain feasible solutions close to the individual best solutions. The proposed approach also allows identifying the dissatisfaction for the involved stakeholders in different feasible solutions. Furthermore, the proposed approach can be easily implemented to solve large optimization problems with multiple objectives.

The proposed approach has been applied to a case study from Mexico. The results showed that a change in the priorities of a stakeholder can produce unsatisfactory solutions for other decision-makers. Furthermore, this approach allows proposing a solution with the lowest dissatisfaction ratio taking into account diverse goals.

Finally, a possible extension for this paper is to account for the involved uncertainty in the demands and prices of biofuels, because variations on these prices can affect seriously the topology of the supply chain. Another extension can be the incorporation of methodologies based on geographic information systems in order to take into account information about locations to be afforested as well as locations with high erosion levels. In addition, an interesting solution alternative to consider different priorities between multiple stakeholders is game theory, which can be applied and compared in future works.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acssuschemeng.8b01937.

> Detailed information for the implemented mathematical model (section S.1), nomenclature (section S.2), and the data for the case study in **Tables S1−S5** (section S.3) (PDF)

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Notes

The authors declare no competing financial interest.

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NOMENCLATURE

Noncomputed Parameters

w_i^{JF} Weight factor for the objective of jobs in eco-industries
w_i^{PR} Weight factor for the objective of profit of refineries
w_i^{PB} Weight factor for the objective of profit of biorefineries
w_i^{PF} Weight factor for the objective of profit of eco-industries
w_i^{ET} Weight factor for the objective of total emissions
w_i^{JR} Weight factor for the objective of jobs of refineries
w_i^{JB} Weight factor for the objective of jobs of biorefineries

Computed Parameters

P^{L-R} Obtained lower bound of refinery profit
P^{U-R} Obtained upper bound of refinery profit
P^{L-B} Obtained lower bound of biorefinery profit
P^{U-B} Obtained upper bound of biorefinery profit
P^{L-F} Obtained lower bound of eco-industry profit
P^{U-F} Obtained upper bound of eco-industry profit
E^{L-T} Obtained lower bound of net emissions
E^{U-T} Obtained upper bound of net emissions
J^{L-R} Obtained lower bound of generated jobs in refineries
J^{U-R} Obtained upper bound of generated jobs in refineries
J^{L-B} Obtained lower bound of generated jobs in biorefineries
J^{U-B} Obtained upper bound of generated jobs in biorefineries
J^{L-F} Obtained lower bound of generated jobs in forest plantations
J^{U-F} Obtained upper bound of generated jobs in forest plantations

Variables

CS_i Compromise solution given for each case of stakeholders
CS* General compromise solution
P^R Refinery profit
P^B Biorefinery profit
P^F Eco-industry profit
E^T Total emissions
J^R Refinery jobs
J^B Biorefinery jobs
J^F Eco-industry jobs
DR Dissatisfaction relation
TJ Total generated jobs
TP Total profit

Indexes

i Index used to denote cases of stakeholders with different priorities

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Sets

I Set containing all elements of index *i*

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