Agrifood Supply Chain Network Design Under Sustainable Development Policies

Carlos Alberto Moreno Camacho

Carlos Alberto Moreno Camacho. Agrifood Supply Chain Network Design Under Sustainable Development Policies. Earth Sciences. Université de Lyon; Université de la Sabana - Colombie, 2021. English. NNT : 2021LYSEM023 . tel-04891733

HAL Id: tel-04891733
https://hal-emse.ccsd.cnrs.fr/tel-04891733v1

Submitted on 9 Feb 2025

N°d'ordre NNT : 2021LYSEM023

THESE de DOCTORAT DE L'UNIVERSITE DE LYON
OPEREE AU SEIN DE
L'Ecole des Mines de Saint-Etienne

Ecole Doctorale N° 488
Sciences, Ingénierie, Santé

Spécialité de doctorat : SCIENCES ET GENIE DE L'ENVIRONNEMENT
Discipline : LOGISTIQUE

THESE EN COTUTELLE INTERNATIONAL AVEC
L'UNIVERSIDAD DE LA SABANA, COLOMBIE
DOCTORADO EN LOGISTICA Y GESTION DE CADENAS DE SUMINISTROS

Soutenue publiquement le 29 juin 2021, par :

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Conception de réseaux de chaînes logistique agroalimentaires dans le cadre de politiques de développement durable

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Mise à jour : 24/11/2020

Acknowledgement

In the following lines, I would like to express my deepest gratitude to all those who have contributed one way or another to the completion of this thesis. May God bless you to a greater extent than my heart may wish.

First, sincere thanks to my advisors, professors Anicia, Natacha, and Jairo. I would like to them for their patience, understanding, and constant disposition to contribute to this work from their different research fields. The variety of their approaches enrich this work and my knowledge of sustainability in operations. I value the support and guidance you have provided to me since the first day. My gratitude also to the reviewers, professors Ana Paula, Blandine, Iván, and Yannick. Their comments on the document and the dynamic discussion during the defense were enriching to my formation.

In addition, I am grateful for the warm welcoming and support of every person at Kedge Business School, staff, students, and professors. I truly appreciate the confidence you showed in me. Thank you for the assistance you provided me during my teaching activities. I appreciated the enriching exchanges and comments during the research group meetings. It helped to establish a clear path and contributions to the research work. Thanks to the professors at Universidad de La Sabana and their assistance during the first half of this program.

I want to thank my friends and classmates, Andrea, Diana, and Esteban. Thank you for being so generous with your ideas in every encounter. Thanks for your support and encouragement. Special thanks to my friends Lore, Felipe, Jeysson, Julián, Jorge, Juan, Milton, L.M. I enjoyed our entertaining conversations. Moreover, almost one-third of this work was done under quarantine. Therefore, I am obliged to my housemates, Ram, Tomoki, Charlotte, Kaitlyn, Bauka, Alex, Clara, and Alice. I appreciate so much your company, your talks during the tough days, and the constant motivation. You were a significant part of this journey.

Finally, I am grateful to my family for their support and encouragement in pursuing this goal. I want to thank them for understanding my absence at important times. I am thankful for the words of encouragement from my mom and dad. Thanks for your unconditional love. I want to thank my brother, his wife, and my beautiful two nieces. You are the best and bring life, joy, and happiness to this family.

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Acronyms

AFOLU	Agriculture, Forestry and Other Land use
CONPES	National Council for Economic and Social Policy - Colombia
DANE	National Administrative Department of Statistics - Colombia
DNP	National Planning Department - Colombia
FAO	Food and Agriculture Organization of the United Nations
FEDEGAN	Colombian Federation of Ranchers
FEPALE	Pan-American Dairy Federation
GDP	Gross Domestic Product
GHG	Greenhouse gas
GWP	Global Warming Potential
ICA	Colombian Agricultural Institute
IDEAM	Institute of Hydrology, Meteorology and Environmental Studies - Colombia
IGAC	Agustin Codazzi Geographical Institute - Colombia
IPCC	Intergovernmental Panel for Climate Change
M.A.S.L	Meters Above Sea Level
MADR	Ministry of Agriculture and Rural Development - Colombia
MADS	Ministry of Environment and Sustainable Development - Colombia
MCIT	Ministry of Commerce, Industry and Tourism - Colombia
MILP	Mixed Integer Linear Programming
NAMA	National Appropriate Mitigation Action
ODS	Ozone-Depleting Substances
OECD	Organization for Economic Co-operation and Development
PTP	Program for productive transformation - Colombia
SCM	Supply Chain Management
SCND	Supply Chain Network Design
SDG	Sustainable Development Goals
SSCND	Sustainable Supply Chain Network Design
UPRA	Agriculture Planning Unit - Colombia
USP	Milk Price Monitoring Unit - Colombia

Abstract

This work addresses the research problem of quantitative support for decision-making in sustainable supply chain network design (SSCND). We first identify the common key indicators utilized to assess sustainability in supply chain design applications. We propose both (*i*) a single-objective and (*ii*) a multi-objective modeling approaches to deal with environmental and social criteria to the design of a supply chain network from a company perspective. Considering a broader perspective of sustainability in supply chains, the unit of analysis is extended from a company perspective to consider a wide-industry perspective for the sector. We specifically consider the effects of policy application on encompassing the sector towards sustainable development and its impacts in the supply network structure.

The purpose of this work is to propose an efficient assessment procedure for the joint assessment of economic, environmental, and social performance for the design or redesign of supply chain network. A mathematical formulation considering the evolution of the supply chain and the construction of capacities in the long term is presented. To this regard, we define sustainability objectives according to the current conditions of the sector and the country. We compare the supply chain structure changes over a time horizon following an ex-ante sustainability assessment approach. Moreover, sustainability key performance indicators are chosen considering current sustainability challenges of the sector. The performance of the model is tested with an application in the dairy industry in a developing-economy country. It illustrates the utility of the model to evaluate national mitigation and adaptation activities in the design of supply chain networks. The need of setting targets when measuring sustainability in the supply chain field is highlighted. Results offer meaningful decision support to policymakers in evaluating implementation of policies and actions, and in the definition of strategical paths towards sustainability.

Keywords: sustainable supply chain, supply chain network design, sustainable development policy, optimization, sustainability assessment, dairy supply chain

Résumé

Cette thèse s’inscrit dans les recherches sur l'aide quantitative à la prise de décision dans la conception de réseaux de chaînes d'approvisionnement durables (SSCND). Dans un premier temp, nous identifions les indicateurs clés communs utilisés dans des publications scientifiques pour évaluer la durabilité dans les applications de conception de chaînes d'approvisionnement. Nous proposons ensuite (i) une approche de modélisation à objectif unique et (ii) une approche de modélisation multi-objectifs pour inclure les critères environnementaux et sociaux dans la conception d'un réseau de chaîne d'approvisionnement du point de vue de l'entreprise. En considérant la perspective plus large de la durabilité dans les chaînes d'approvisionnement, l'unité d'analyse est étendue d'une perspective d'entreprise pour considérer l’ensemble d’une filière au sein des différentes régions d’un pays donné. En particulier, nous étudions les effets de la mise en œuvre des politiques de développement durable sur la structure du réseau d’approvisionnement pour l’industrie laitière en Colombie.

L'objectif de ce travail est de proposer une procédure efficace d'évaluation conjointe des performances économiques, environnementales et sociales pour la conception ou la reconception d'un réseau de chaînes d'approvisionnement. Une formulation mathématique est présentée, qui tient compte de l'évolution de la chaîne d'approvisionnement et du renforcement des capacités à long terme. Nous proposons une approche d'évaluation ex ante de la durabilité pour comparer les changements dans la structure du réseau de la chaîne d'approvisionnement en vue d’atteindre les objectifs de durabilité. En outre, les indicateurs clés de performance en matière de durabilité sont choisis en tenant compte des défis actuels du secteur en matière de durabilité. La performance du modèle est testée avec une application dans l'industrie laitière d'un pays à économie en développement. Elle illustre l'utilité du modèle pour évaluer les activités nationales d'atténuation et d'adaptation dans la conception des réseaux de chaînes d'approvisionnement. La nécessité de fixer des objectifs pour mesurer la durabilité dans le domaine de la chaîne d'approvisionnement est soulignée. Les résultats offrent une aide à la décision significative aux décideurs politiques dans l'évaluation de la mise en œuvre des actions et la définition des voies stratégiques vers la durabilité.

Mots clés : conception de réseaux de supply chains, politique de développement durable, supply chain durable, optimisation, évaluation de la durabilité, industrie laitière.

Introduction (en français)

En 1987, la publication "*Notre avenir à tous*" de la Commission mondiale sur l'environnement et le développement des Nations unies a ouvert, au niveau mondial, le débat sur le développement durable et la durabilité (CMED, 1987). À ce moment-là, le document définissait le développement durable comme "un développement qui répond aux besoins du présent sans compromettre la capacité des générations futures à répondre à leurs propres besoins." Selon (Ferrer, 2008), la simplicité de cette définition et son caractère inspirant ont permis l'utilisation généralisée de ce concept par les universitaires, les praticiens et les contextes politiques. De légères variations de cette définition sont couramment utilisées pour définir la durabilité. Par exemple, l'appropriation du concept de développement durable dans le milieu des affaires a conduit John Elkington à inventer le terme Triple Bottom Line (TBL) (Elkington, 1994, 2013). L'auteur souligne comment les stratégies durables peuvent bénéficier simultanément aux entreprises et aux clients, ainsi qu'à l'environnement, ce qui incite les entreprises à comptabiliser leurs gains et leurs pertes non seulement en termes économiques, mais aussi en termes environnementaux et sociaux.

Comme indiqué par Allaoui, Guo, Choudhary, & Bloemhof (2018), les décisions concernant l'emplacement des installations, la détermination de la capacité, la sélection de la technologie, la sélection du mode de transport qui sont, entre autres, impliquées dans le problème de conception de réseau de chaîne d'approvisionnement correspondent à l'une des principales décisions au niveau stratégique ayant un impact sur la performance économique, environnementale et sociale d'une chaîne d'approvisionnement à long terme. Par exemple, d'une part, la construction d'une usine de fabrication dans une région spécifique peut générer de nouvelles opportunités de travail, promouvoir le développement de l'infrastructure routière, déclencher l'arrivée d'habitants dans la région et encourager le développement de services sociaux. D'autre part, elle peut menacer l'écosystème de la région, en raison de la consommation d'eau, de l'utilisation des terres, de la pollution, de l'élimination des déchets et, d'une manière générale, de la pression accrue sur les ressources naturelles et les services sociaux, ce qui a des répercussions sur l'environnement et entraîne une diminution du bien-être social.

En raison de la multiplicité des contextes et des caractéristiques de l'environnement des entreprises, des marchés et des parties prenantes, le problème de l'évaluation de la performance de durabilité d'un réseau de chaînes d'approvisionnement ne peut pas être abordé de manière générique (Brandenburg, Govindan, Sarkis, & Seuring, 2014). Pour le dire autrement, puisque les défis du développement durable ne sont pas les mêmes pour toutes les industries, il apparait fondamental de développer des études personnalisées considérant les particularités de l'industrie et de son territoire. Par exemple, la consommation d'eau peut ne pas être aussi pertinente dans le secteur bancaire que dans les systèmes alimentaires. ,De plus, tous les secteurs d’activités n’ont pas fait l’objet de la même attention dans la littérature scientifique. Par exemple Grant, D. B., Trautrims, A. et Wong (2017), ont montré que, dans la littérature, il existe de nombreuses études développées dans les cas de l'industrie manufacturière, tandis que le secteur agricole a reçu moins d'attention, malgré les caractéristiques sociales documentées des moyens de subsistance des agriculteurs et la contribution représentative du secteur dans les émissions totales de gaz à effet de serre (GES) au niveau mondial.

Dans de nombreux pays, notamment dans les pays en développement, le secteur agroalimentaire joue un rôle essentiel dans l'économie en étant un contributeur important au produit intérieur brut (PIB) (Gebresenbet & Boso, 2012) et il constitue un agent essentiel du développement économique, social et environnemental durable des communautés rurales (Naik & Suresh, 2018). Selon la Banque mondiale, ce secteur représentait près d'un tiers du PIB mondial en 2014 (World Bank Group, 2015). De plus, en raison de la croissance démographique, des progrès des transports, des technologies de l'information et de la communication, le secteur agricole a connu un taux de croissance annuel de plus de 6% au cours de la dernière décennie, et sa production devrait être multipliée par deux d'ici 2050 (FAO, 2018). Dans son sens le plus large, l'industrie agricole comprend un large ensemble de procédures et services connexes, dans lequel les ressources naturelles sont utilisées pour produire des produits de base tels que les aliments, les fibres, les carburants et les produits forestiers, entre autres. Plus précisément, les chaînes d'approvisionnement agroalimentaires comprennent une série d'activités allant de la production à la distribution pour amener les produits agricoles de la ferme au marché. Les chaînes d'approvisionnement agroalimentaires ont des impacts environnementaux spécifiques qui influent sur l'atteinte des limites planétaires, telles que les émissions de gaz à effet de serre, l’impact sur la biodiversité, le changement d'utilisation des sols, la consommation d'eau, les effets sur les cycles du phosphore et de l'azote (Boutaud et Gondran, 2020), l'élimination des déchets, le développement social, entre autres, qui deviennent des facteurs pertinents dans la configuration du réseau.

À ce stade, trois aspects ressortent du champ de recherche sur la conception des réseaux de chaînes d'approvisionnement. Premièrement, bien que l'évaluation de la durabilité revendique une vision holistique de la chaîne d'approvisionnement, elle se concentre parfois sur les opérations en aval et les impacts provenant des fournisseurs en amont sont souvent omis, y compris lorsque des activités agricoles ont lieu à ce niveau. Ce phénomène peut conduire à des solutions superficielles ayant un faible impact sur la durabilité de la chaîne d'approvisionnement. Deuxièmement, la plupart des travaux considèrent une perspective de durabilité centrée sur l'entreprise ; les approches du développement durable à l'échelle de la filière sont rares. Des études récentes ont suggéré que les améliorations environnementales progressives apportées par les entreprises individuelles peuvent être inadéquates pour faire face aux problèmes environnementaux mondiaux. À cet égard, les organismes publics sont appelés à être les points de connexion entre les objectifs de développement durable et les stratégies de gestion de la chaîne d'approvisionnement des entreprises, afin de transposer les aspirations mondiales dans les contextes régionaux et locaux (Paletta, Foschi, Alimehmeti, & Bonoli, 2021).

En fonction de ces considérations, ce travail présente un modèle intégré pour évaluer les dimensions économiques, environnementales et sociales, tout en tenant compte des politiques sectorielles et nationales en matière d'environnement et de développement. Au lieu d'avoir une perspective de chaîne d'approvisionnement d'entreprise, le modèle est destiné à travailler dans la macro localisation des capacités dans une perspective de large industrie. Le présent travail envisage plusieurs approches de formulation pour traiter la conception de la chaîne d'approvisionnement lorsque les facteurs environnementaux et sociaux sont pris en compte dans le processus de prise de décision. Il explore les formulations à objectif unique et multi-objectifs. Le travail souligne l'impact des critères de durabilité sur la structure de la chaîne d'approvisionnement, et discute de la nécessité de définir des objectifs pour évaluer la durabilité au niveau de la chaîne d'approvisionnement. Enfin, il présente un modèle mathématique visant à effectuer une évaluation ex ante de la durabilité au niveau de l'ensemble de la filière pour la définition de la structure de la chaîne d'approvisionnement, dans le cadre du développement de politiques ou d'actions. Le modèle représente la structure de la chaîne d'approvisionnement, au cours de l'horizon temporel jusqu'à ce qu'elle atteigne les objectifs spécifiés à atteindre. Bien que le modèle puisse être appliqué à plusieurs secteurs, ce travail présente un cas spécifique pour l'industrie laitière en Colombie.

La structure du document

Cette thèse est organisée en huit chapitres comme présenté dans la Figure 0.1. Le chapitre 1 énonce notre problèmatique de recherche, les objectifs de la recherche et décrit la méthodologie de l'étude. Le chapitre 2 présente la revue de la littérature, la réflexion, les paramètres d'évaluation de la durabilité, les approches de solutions et les applications. Le chapitre 3 présente un modèle de programmation linéaire en nombres entiers mixtes (MILP) avec une approche de solution axée sur les dimensions. Ici, trois objectifs différents portant sur les dimensions économiques, environnementales et sociales sont évalués pour comparer l'impact sur la structure du réseau lorsque la décision est guidée par un seul critère d'évaluation. Les résultats montrent comment la structure du réseau affecte les facteurs économiques, environnementaux et sociaux. Ils montrent également comment les préférences dans une dimension représentent des compromis dans les deux autres ou au moins dans l'une d'entre elles.

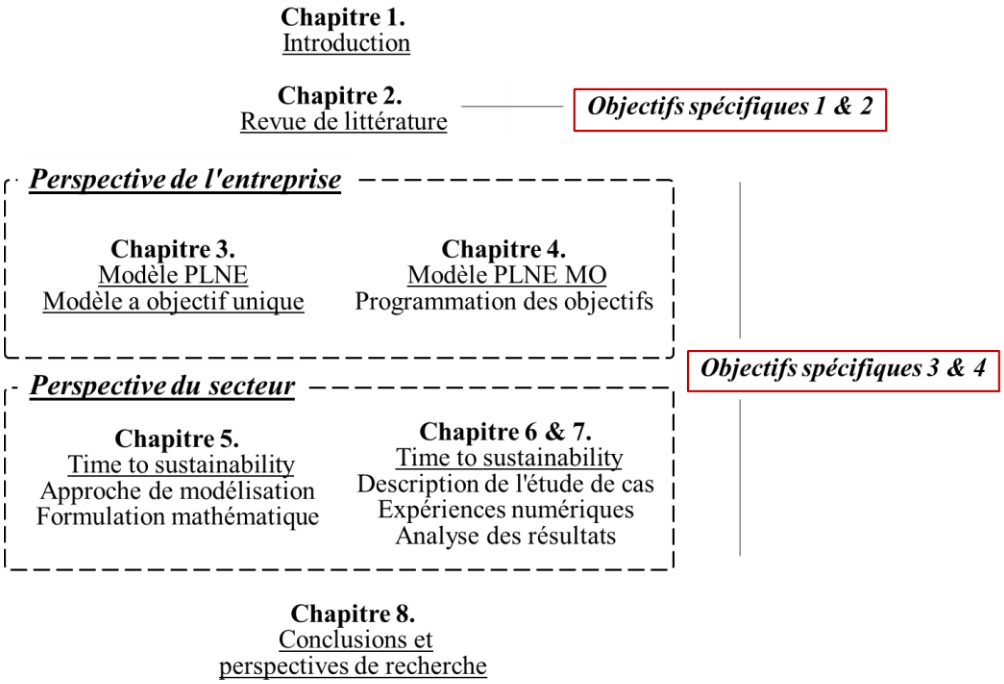

Figure 0.1. Structure du document

Le chapitre 4 présente une approche de modélisation multi-objectifs pour la conception de chaînes d'approvisionnement durables. Contrairement à d'autres approches dans lesquelles les préférences du décideur sont incluses, ce chapitre présente une approche de programmation d'objectifs de Chebyshev sans préférence. Au lieu d'attribuer des pondérations à chaque objectif ou de limiter leur aggravation, l'approche de Chebyshev estime la meilleure solution possible en minimisant la distance maximale à la solution idéale pour chaque objectif. L'idée derrière cette approche était d'inclure les critères dans une modélisation mathématique en évitant d'adopter une mentalité de compromis ou une approche de durabilité faible.

Le chapitre 5 présente une description générale de l'étude de cas et de son importance dans le contexte écologique et le développement social du pays. Il présente également une définition de la durabilité pour le secteur à partir de laquelle les indicateurs de durabilité proposés sont dérivés. Le chapitre 6 présente un modèle mathématique pour la conception d'une chaîne d'approvisionnement dans une perspective industrielle large, tout en considérant l'exécution de politiques et d'actions. Au lieu de considérer des objectifs multiples, l'approche considère le temps nécessaire pour atteindre des valeurs définies pour un ensemble d'indicateurs clés dans les trois dimensions de la durabilité. La performance du modèle est évaluée à l'aide d'une étude de cas dans l'industrie laitière de la Colombie au chapitre 7. Les résultats du modèle sont utiles pour la définition des capacités et de la localisation des installations de production, de transformation et de distribution, dans tout le pays. Les conclusions et les perspectives de recherche sur le lien entre la durabilité et la conception de la chaîne d'approvisionnement sont discutées au chapitre 8.

Les conclusions

Cette thèse aborde le problème de la conception d'un réseau de chaînes d'approvisionnement en tenant compte des facteurs sociaux, environnementaux et économiques. Pour traiter ce problème, différentes approches de modélisation sont proposées au cours du développement du projet. En effet, cette thèse explore des approches de modélisation mono-objectif et multi-objectifs, en utilisant des indicateurs individuels et composites pour représenter les critères de durabilité au niveau de la chaîne d'approvisionnement et discuter de leurs applications, opportunités et défauts. Contrairement à d'autres études sur le sujet, qui se concentrent principalement sur le développement d'algorithmes efficaces sur le plan informatique, ce travail est en outre centré sur la discussion de la durabilité et du lien entre la gestion de la chaîne d'approvisionnement et l'évaluation de la durabilité. En particulier, ce travail s'intéresse spécialement à l'évaluation de la durabilité dans les décisions stratégiques de la chaîne d'approvisionnement sous l'application de politiques.

Reconnaissant le lien entre le développement durable et l'évaluation de la durabilité, cette thèse commence par présenter une revue sur le problème de conception de réseaux de chaînes d'approvisionnement, avec un intérêt intentionnel pour la compilation des métriques incluses dans le problème à traiter avec des critères économiques, environnementaux et sociaux. Le travail a été principalement axé sur l'évaluation des indicateurs utilisés dans l'application réelle du problème de conception de réseaux. La revue présente les critères les plus courants utilisés pour représenter les différentes catégories dans les trois dimensions de la durabilité. En bref, elle identifie la performance financière comme étant la catégorie la plus prédominante dans la gestion de la chaîne d'approvisionnement pour évaluer la durabilité au niveau économique, la pollution atmosphérique dans la dimension environnementale, et dans la dimension sociale, les catégories les plus influentes sont les conditions de travail et le développement social.

Ce travail considère l'évaluation de la durabilité au niveau de la chaîne d'approvisionnement sous deux angles différents. D'une part, il considère une vision de la durabilité de l'entreprise au niveau de l'optimisation de la planification de l'approvisionnement. Dans le chapitre 3, nous présentons une approche axée sur les dimensions, un MILP pour la conception d'un réseau de chaîne d'approvisionnement générique. Le modèle est résolu en considérant trois objectifs différents, un pour chaque dimension de la durabilité. Les résultats montrent l'effet des critères de décision sur la structure de la chaîne d'approvisionnement. Il est utile de reconnaître la capacité d'amélioration de la chaîne d'approvisionnement en calculant des valeurs idéales pour chaque dimension considérée. En outre, il expose l'impossibilité de les atteindre toutes en même temps en raison de la nature conflictuelle des objectifs. Le chapitre 4 présente une approche multi-objectifs pour traiter l'inclusion synchronisée des critères de durabilité. Nous discutons des différentes approches multi-objectifs dans la littérature académique et de leurs façons de traiter les préférences des décideurs. En outre, nous discutons de certaines lacunes liées à l'absence d'objectifs définis pour chaque dimension de l'évaluation de la durabilité. Le modèle est résolu à l'aide d'une approche de programmation par objectifs de type Tchebychev. L'approche de la solution sans préférence a conduit à une solution faisable sans établir de préférences biaisées sur les objectifs. Mais, plus important encore, elle ouvre la discussion sur les objectifs et l'horizon temporel en considérant le développement durable dans les chaînes d'approvisionnement.

D'autre part, ce travail aborde la durabilité dans une perspective industrielle au sens large. Ce travail discute de la nécessité d'une vision holistique de la durabilité dans les décisions à long terme au niveau de la chaîne d'approvisionnement, étant donné que les efforts séparés et individuels des entreprises pourraient ne pas entraîner la réduction des émissions qui est nécessaire pour atteindre les engagements nationaux et mondiaux en matière de changement climatique et de développement durable. Par conséquent, ce travail contribue à la définition d'un modèle d'évaluation ex ante de la durabilité pour la conception du réseau d'approvisionnement dans le secteur laitier en Colombie présenté au chapitre 6. Le modèle multi-période traite de la méga-localisation des installations de production, de transformation et de distribution pour atteindre un ensemble d'objectifs de durabilité sous l'application de politiques et d'actions. Contrairement aux travaux antérieurs adoptant une recherche de compromis sur les performances économiques, environnementales et sociales, le modèle vise à atteindre un objectif défini pour les indicateurs clés définis dans chaque dimension de la durabilité, en modifiant la structure de la chaîne d'approvisionnement sur un horizon temporel. En tant qu'aspect novateur de la modélisation, l'évaluation inclut l'utilisation des terres pour les activités agricoles et leur transformation en pratiques durables.

Cette thèse contribue à la discussion sur l'évaluation de la durabilité et sur la nécessité d'établir des objectifs de durabilité lors de la prise de décisions relatives à la gestion de la chaîne d'approvisionnement, en particulier lors de la conception de la chaîne d'approvisionnement. Comme indiqué par (Pope, Annandale, & Morrison-Saunders, 2004), l'évaluation de la durabilité nécessite un concept de durabilité bien défini. Les efforts risquent d'échouer à présenter des solutions alternatives lorsque les objectifs ne sont pas définis. À cet égard, ce travail souligne la pertinence de l'évaluation des améliorations dans un contexte où les cibles ou les objectifs souhaités sont discutés. En outre, il examine la définition des indicateurs clés de performance de la durabilité en fonction de ce que la durabilité signifie pour les parties prenantes dans le cas d'étude spécifique présenté ici.

La performance du modèle d'évaluation de la durabilité ex-ante est testée sur une étude de cas en Colombie, une économie en développement, avec des données réalistes provenant des syndicats et des entités publiques du pays. Peu de travaux ont pris en compte une perspective industrielle large pour l'évaluation de la durabilité dans la conception des chaînes d'approvisionnement et, à notre connaissance, aucun travail n'a présenté un modèle de durabilité ex ante pour l'évaluation des politiques à long terme et ses impacts sur la structure industrielle. Les résultats de ce travail mettent en évidence le lien entre la durabilité et les outils de mesure de la durabilité au niveau de la chaîne d'approvisionnement. Il est possible de travailler au développement de modèles non génériques qui évaluent la durabilité tout en considérant des objectifs réalisables dans chaque dimension observée.

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Chapter 1 Introduction

In 1987, the publication "*Our common future,"* from the World Commission on Environment and Development of the United Nations opened, at the global level, the discussion about sustainable development and sustainability as a final goal (WCED, 1987). To that moment, the document defined sustainable development as "*development that meets the needs of the present without compromising the ability of future generations to meet their own needs*." In accordance with (Ferrer, 2008), the simplicity of this definition and its inspirational character have permitted the widespread use of that concept by academics, practitioners, and political contexts. Slight variations of this definition are commonly used to define sustainability. For instance, Kannegiesser & Günther (2014) refers a definition of sustainability in the business context that was previously presented by the International Institute for Sustainable Development (IISD) as "*-adopting business strategies and activities that meet the needs of the enterprise and its stakeholders today while protecting, sustaining and enhancing the human and natural resources that will be needed in the future."* However, as pointed out by (Bryceson & Ross, 2020), the concept of sustainability has way different meanings when it is addressed by environmentalists, business managers, social scientists, and other fields (Daly, 2006). There are so many definitions that it is necessary to define the concept in every context it is used.

For instance, the appropriation of the sustainable development concept in the business environment took John Elkington to coin the term *Triple Bottom Line* (TBL) (Elkington, 1994, 2013). The author emphasizes how sustainable strategies may benefit companies and customers simultaneously and the environment, motivating companies to account for its gain and losses in economic terms and to measure their gains and losses in environmental and social terms. Over the last years, the TBL concept has rapidly spread out in the supply chain management research field as reflected in the increasing number of papers addressing sustainability in general supply chain management. It addresses issues at operational, tactical and strategical level, such as sourcing, production, inventory, transportation management, and network design (Anvari & Turkay, 2017; Devika et al., 2014; Montoya-Torres, 2015; Moreno-Camacho et al., 2019; Mota et al., 2015).

Decisions related to location, capacity, operation technology of facilities, and transportation mode are involved in the supply chain network design problem (SCND). It corresponds to one of the most determining decision at strategic level. As stated by Allaoui, Guo, Choudhary, & Bloemhof (2018), these decision affect economic performane of the company. Also, they have a larger impact on the company's environmental and social performance in the long term. For instance, on one hand, the construction of a manufacturing plant in a specific region can generate new labor opportunities, promote the development of road infrastructure, trigger the arrival of inhabitants into the region and encourage the development of social services facilities. On another hand, it might result in a threat to the region's ecosystem, due to consumption of water, use of land, pollution, waste disposal, and in general, amplified pressure on natural resources and social services, which results in environmental impacts and decreasing of social well-being.

Supply chain network design problem has received increasing attention over the last decades, as shown by multiples review on this issue (Barbosa-Póvoa et al., 2018; Bubicz et al., 2019; Eskandarpour et al., 2015; Xu et al., 2019). Having the current complexity of worldwide production-distribution network, sustainable development is not narrowed to a focal company perspective. Instead, a holistic view of the entire network is needed. Consequently, action planning having impact on financial resources, natural resources and stakeholders involves each actor in the supply chain, from the initial producers of raw material to the end-user customers, to design or redesign their processes (Montoya-Torres et al., 2015; Touboulic & Walker, 2015; Wolff et al., 2017). Moreover, due to the multiplicity of contexts and characteristics of businesses environment, markets, and stakeholders, the problem of assessing sustainability performance of a supply chain network cannot be addressed in a generic way (Brandenburg et al., 2014). To put it differently, since challenges to sustainable development are not equal in every industry, it results fundamental to develop customized studies considering the particularities of the industry and its territory. For instance, water consumption might not be that relevant in banking as it is for food systems.

In this regard, it is observed that bioenergy is one of the sectors receiving more interest from academics. Notably, most of the case studies published in academic literature focus on the “biomass to bioenergy” industry, which links the agricultural and the industrial sectors seeking to partially replace fossil fuels by more sustainable energy sources (Eskandarpour et al., 2015). Findings of these research highlight that most of the studies focus on generic environmental impacts coming from the distribution process and facilities location, but factors in both environmental and social dimensions in the agricultural sector are scarcely involved into the decision-making process. Indeed, Grant, D. B., Trautrims, A. and Wong (2017) stated that, in the literature, there are numerous studies developed in the manufacturing industry , while the agricultural sector has received less attention. Despite the documented social characteristics of farm livelihood and the representative contribution of the sector in the total greenhouse gas (GHG) emissions at global level.

In many countries, especially in developing countries, agri-food sector plays an essential role in the economy by being a significant contributor to gross domestic product (GDP) (Gebresenbet & Boso, 2012). It constitutes an essential agent in the economic, social and environmentally sustainable development of rural communities (Naik & Suresh, 2018). According to the World Bank, this sector accounted for almost one-third of global GDP in 2014 (World Bank Group, 2015). Moreover, due to population growth, advances in transport, information, and communication technology, the agricultural sector has an annual growth rate of over 6% during the last decade. Its production is expected to twofold by 2050 (FAO, 2018). The sector is especially important in Latin America and the Caribbean region. It represents 14.1% of total generated employees in the region in 2018 (OECD/FAO, 2019), meanwhile in the European Union it accounted about 4.4% of total employment by 2017 (Eurostat, 2019). Despite the economic growth of agri-food sector in the last years, rural areas still tending to lag in social and economic conditions. For instance, according to the European Comission (2007), incomes in rural areas are near 20% lower than in urban areas, and rural areas present higher unemployment rates. Agri-food sector also plays a significant role in the environment. Agriculture, forestry and land-use change account for 25% of GHG emissions. Part of the solution to climate change is therefore in the mitigation in the agriculture sector.

In its broadest sense, the agricultural industry comprises a width set of procedures and its related services. Natural resources are used to produce commodities such as food, fiber, fuels, and forest products, among others. Specifically, agri-food supply chains comprise a series of activities from production to distribution to bring farm products from farms to markets. There are unique characteristics of agri-food supply chains affecting sustainability such as soil use change, water consumption, effects on the phosphorus and nitrogen cycles, waste disposal, and social development. These become relevant factors at determining location for production facilities and en up affecting the configuration of network.

At this far, three aspects stand out on the SCND research field. First, although sustainability assessment claims for a holistic view of the supply chain, it focuses sometimes on downstream operations and impacts coming from upstream suppliers might be sidelined, especially when agricultural activities occur at this level. This phenomenon might lead to superficial solutions with low impacts in supply chain sustainability. Second, most works consider a focal corporate sustainability perspective; wide-industry approaches to sustainable development are scarce. Recent studies have suggested that incremental environmental improvements carried out by individual companies may be inadequate to contend with global environmental issues. In this regard, public organizations are called to be the connecting points between the sustainable development goals and corporate supply chain management strategies, to bring global aspirations into regional and local contexts (Paletta et al., 2021).

Last but not least, surprisingly, few studies consider goals and targets at defining sustainable alternative solutions (Robert et al., 2005). Most of the works focus on developing models to the design of more eco-friendly or socio-friendly structures. Although clearly the new yielded solution represents an improvement compared with the first state, no further analyses are done to confirm that the new solution meets some requirements in the context to be considered sustainable. Therefore, an integrated perspective of supply chain design is needed. In order to assess sustainability criteria into the SC, (i) suitable metrics for the three dimensions of sustainability must be appropriately defined; (ii) it is required the definition of sustainability objectives and indicators to compare performance from different configurations; and (iii) suitable models need to be developed to optimize the multi-dimensional performance of sustainable supply chains (Beske-Janssen et al., 2015).

According to these considerations, this work presents an integrated model to assess economic, environmental, and social dimensions, while considering environmental and development sectorial and national policies. Instead of having a corporate supply chain perspective, the model is intended to work in the macro location of capacities in a wide-industry perspective. The present work considers multiple formulation approaches to deal with supply chain design when environmental and social factors are considered into the decision-making process. It explores single-objective and multi-objectives formulations. The work highlights the impact of sustainability criteria on supply chain structure and discuss the urge to define targets at assessing sustainability at supple chain level. Finally, it presents a mathematical model useful to carry out an ex-ante sustainability assessment at the wide industry level to define the supply chain structure, under development of policies or actions. The model defines the evolution of the supply chain structure during the time-horizon until it reaches the specified targets. Although the model could be applied to several sectors, this work presents a specific case in the dairy industry in Colombia.

This work contributes to developing mathematical models to the design of supply chain network structures under the evaluation of policies or actions. Moreover, it presents a way to define targets for assessing sustainability in the long-term within the supply chain context, based on global commitments. This work also presents an application of the model to a case study in the agri-food industry considering a wide-industry perspective.

1. Research objectives

The main objective of this research work is to present a support decision-making model for the evaluation of policies and its impacts in supply chain network design in the agri-food industry, while accounting for economic, environmental, and social factors. The objectives formulated for this research project are as follows:

General objective

To propose an efficient assessment procedure to the joint evaluation of the economic, environmental, and social performance of supply chain network design for agri-food based products.

Specific Objectives

1. To identify the more relevant attributes and strategic decisions affecting sustainable development in the agri-food based product supply chain.
2. To identify accurate assessment methodologies either quantitative or qualitative for assessing social and environmental impacts of agri-food based products supply chain.
3. To propose a solution method based on quantitative tools for the design of agri-food based products supply chain network when considering criteria within the three dimensions of sustainability
4. To validate the proposed solution methods through numerical experiments from a case study in Colombia to compare and analyze its business and societal impacts.

2. Journey description

This thesis is organized into eight chapters as presented in Figure 1.1. *Document structure*

. Chapter 1 (this chapter) stated the general problem to be studied and the objectives. It also includes the methodological approach of the study (see next Section). Initially, four research questions guided the development of the project. The following is a description of how these questions were addressed and how the development of the research work responds to them. It should be noted that additional questions appeared during the research development and were useful in defining the scope and limitation of this work.

As mentioned before, plenty of work has been developed to link sustainability and supply chain network design (SCND). Sustainability has become a cornerstone to the development of supply chain management research field. In the first instance, our objective was to get to know better that works and to find:

(i) What are the relevant sustainability factors to address when designing agri-food based product supply chain network?

(ii) How can those factors be accurately measured to assess the performance of the supply chain and its environmental and social impacts?

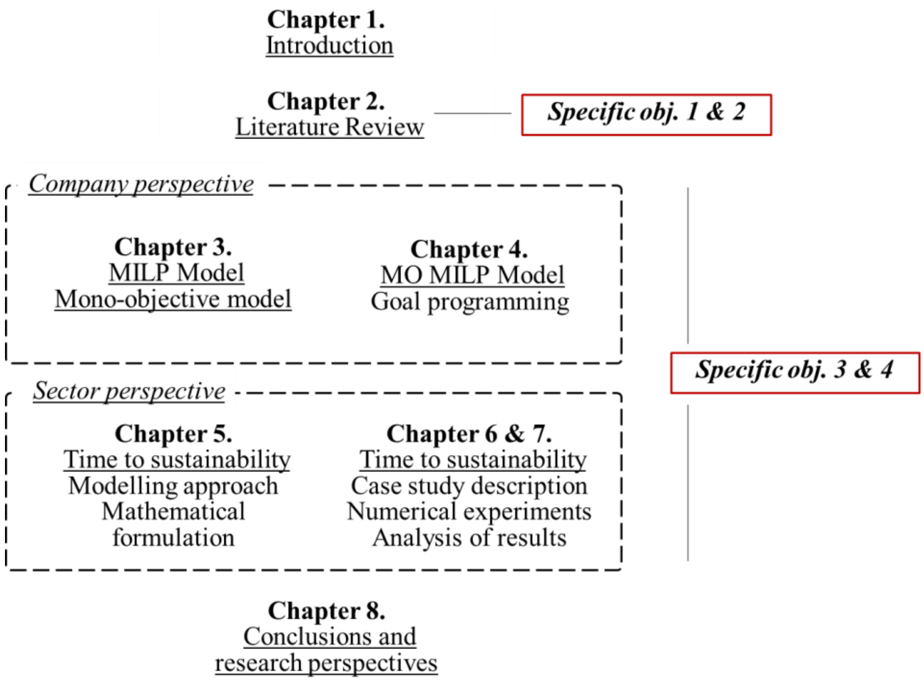

Figure 1.1. Document structure

To this purpose a systematic literature review was carried out with a specific scope in metrics and measurement methods for sustainability assessment in SCND. In the academic literature, reviews in the field of sustainability and supply chain management might be classified according to its scope in five categories (*a*) Summary of progress and trends in SSCM, (*b*) Tracking sustainability concept and its evolution in the SC field, (*c*) Solution methodologies for SSCM, (*d*) Review on specific supply chain activities with sustainability purpose, and (*e*) Sustainability performance measurement and identification of metrics. The literature review on this project belongs to category (*e*) and it is presented in Chapter 2. For presenting a complete state of the art in the matter, other relevant articles have been added to the literature review chapter in this document, since they might be excluded from the intended scope of the initial review.

The main objective of the review is to identify both, the common indicators to assess sustainability in supply chain design in different sectors, and how they can be assessed (Moreno-Camacho et al., 2019). The review was also useful to confirm that the lowest attention has been given to the agricultural sector. Therefore the definition of specific metrics for agricultural sector needed deeper inquire. Remaining two questions were:

(iii) How can these metrics or performance indexes be involved in analytical models to better decision-making in the supply chain network design problem? and

(iv) What are the differences in outcomes when sustainability metrics are involved in the design of a supply chain network?

Models in Operations Research dealing with sustainability might be classified as single-objective models and multi-objectives models. Those two approaches were addressed in this thesis. Chapter 3 presents a mixed-integer linear programming (MILP) model with a dimension-driven solution approach. Here, three different objectives addressing economic, environmental, and social dimensions are evaluated to compare the impact on the network structure when the decision is guided by only one evaluation criterion. The results show how network structure affects economic, environmental and social factors. It also shows how preferences in one dimension represent compromises in the remaining two or at least one of them. From this work, new questions arise, for instance, facing different configurations, *which one is sustainable? how to define targets to these criteria?* among others.

Classical approach to the inclusion of preferences in mathematical model is addressed by multi-objective optimization. Chapter 4 presents a multi-objective modeling approach to sustainable supply chain design. Unlike other approaches where decision-maker preferences are included, this chapter presents a non-preference Chebyshev goal programming approach. Instead of receiving weights to each objective or to limit worsening to them, Chebyshev approach calculates the best possible solution at minimizing the maximum distance to the ideal solution for each objective. The idea behind the approach was to include the criteria into a mathematical modeling avoiding adopting a trade-off mentality or a weak sustainability approach. As mentioned by (Elkington, 2018), TBL term might get misinterpreted by early adopters, as long as, instead of encouraging business to track and manage economic social and environmental value added, application fell short by adopting a trade-mentality, considering it as an accounting tool. Here new questions came out: *how long it takes to get from the initial structure of the supply chain to the new recommended structure? Is it a sustainable configuration? Isolated improvements by one company are enough to reach sustainable development?* Other questions related to measurement methodologies appeared as well, for example: *what are the advantages or disadvantages of using composite criteria to assess sustainability?* Or *how to define challenging enough and realistic targets for assessing sustainable development?*

Going forward from that point, represented a challenge to bring to this work insights and perspectives of sustainability from other several disciplines. For example, to give a satisfactory answer to question (*i*) and (*ii*), a specific research of criteria for assessing sustainability in agriculture was carried out. At that point, the inspiring work of (de Olde et al., 2016) takes us to a completely new world in which we were introduced to a full variety of sustainability assessment tools, including the efforts of (Bélanger et al., 2015; Djekic et al., 2014; Elsaesser et al., 2015; Grenz et al., 2009; Lebacq et al., 2013; Paracchini et al., 2015; van Calker et al., 2006; Van Cauwenbergh et al., 2007; Zahm et al., 2008). The influence of these works is reflected in Chapter 5. It presents a wide context of the case study, at defining what sustainability means for stakeholders and participants in the dairy supply chain in Colombia. It also presents the key performance indicators for the evaluation of sustainability considering supply chain network design. Till that point on, the scope of the research goes from corporate perspective to a sectorial perspective.

During the development of this project, relevant political actions, related with sustainable development and climate change, have taken place. Particularly, in the context of the United Nations Framework Convention on Climate Change, and specifically COP21 in Paris. The Intended National determined contributions reports have been in construction and the initial version of National determined contribution (NDC) have been submitted by December 2020, following the Paris Agreement. NDC's present the auto-imposed compromises of the parties to transform their development trajectories to set the world on a course towards sustainable development. It displays each country's strategy, plans, and actions to reduce national emissions and adapt to the impacts of climate change providing numerical mitigation targets for 2025 and/or 2030 (United Nations, 2015). For more details the interested reader is referred to the NDC Registry, hosted in https://www4.unfccc.int/sites/NDCStaging/Pages/Home.aspx.

The NDC’s time horizon is compatible with the proposed Agenda for Sustainable Development but more important it is useful to determine a framework for the definition of goals in the seeking of sustainable development. Based on this, Chapter 6 presents a mathematical model to the design of a supply chain with a wide-industry perspective, while considering the execution or policies and actions. Instead of considering multiple objectives, the approach considers the required time to reach defined values for a set of key indicators in the three dimensions of sustainability. The performance of the model is evaluated using a case study in the dairy industry of Colombia in Chapter 7. The model results are useful to the definition of capacities and location for production, processing, and distribution facilities throughout the country. To close this thesis, conclusions and further research on the link between sustainability and supply chain design are discussed in Chapter 8.

3. Methodology approach

In general terms, several types of research methodologies are available: qualitative, quantitative and mixed, this last combining the two previous ones (Gómez, 2006). The present research work is a quantitative study that involves collecting and qualitative data analysis to answer the research question and the analysis of results to describe and explain part of the problem under study. This research can also be classified as descriptive-explanatory. It is descriptive because it identifies relevant aspects of the research universe, pointing out alternatives that promote the enhancement of decision-making processes for the actors involved in the design of a sustainable supply chains through the implementation of a practical methodology for its design and the evaluation of economic, social and environmental indicators.

Descriptive research works on realities, aiming at the description, registration, analysis, and interpretation of the current nature of a process or phenomenon to provide a correct interpretation (Rodriguez Moguel, 2005). This research aims to characterize the problem of sustainable design of supply chains in the agri-food sector, the impact of these indicators on the chain's strategic decisions, and, based on these descriptions, a solution model is proposed. Based on the latter, this study is also explanatory since it explains the variables and parameters that intervene in the problem, under a strategic approach for the design of logistics chains.

This research provides new insights for the solution of this problem at considering public policies and national development targets in the definition of supply chain structures. Finally, the objective is that future research on the subject will allow the concepts and approaches formulated in the new approach proposed in this work to be deepened. It is worth noting that this research is not intended to study the social behaviors, attitudes, beliefs, ways of thinking and acting of a group or collectivity. The approaches made to the developed model to support the decision making process in the design of sustainable supply chains will not be related to individual beings (e.g., administrative staff, clients, etc.), but to the technical aspects associated with the design of the chain and its impact at strategic level on decision making and on the economic, social and environmental indicators evaluated.

The addressed research problem also corresponds to the type of applied research. Indeed, since applied research is oriented towards solving practical problems in the delineated area (Eyssautier de la Mora, 2006), this research seeks to propose a model for a specific problem, in specific circumstances. It should be noted that the direct application of the models and methods of the proposed solution in this research was for the dairy industry, in Colombia. To validate the model, it is proposed to use the case study methodology. Case study research has been widely used to validate decision support models in Operations Research (Voss et al., 2002). As it has been established in the academic literature, a case study can be taken as the unit of analysis in specific research processes mainly of exploratory type, in which the variables are still unknown and the phenomenon studied is not fully understood, facilitating the case study to reach a higher level of understanding (Voss et al., 2002).

4. Overview of publication outputs

The outputs of this research have been presented at three international conferences, two works have been published and two more are submitted to review in academic journals by the time this manuscript was written. Table 1.1 gives an overview of publications and presentations, and their link with the different chapters of this manuscript.

Table 1.1. Publication outputs of this research

Reference	Publication type	Indexed	Related chapter
C.A. Moreno-Camacho, J.R. Montoya-Torres, A. Jaegler, N. Gondran, "Sustainability metrics for real case applications of the supply chain network design problem: A systematic literature review", Journal of Cleaner Production, Vol. 231, September 2019, pp. 600-618.	Journal paper (published) 19 citations in Scopus up to March 29, 2021	JCR: Q1 Scopus: Q1	Ch. 2
C.A. Moreno-Camacho, J.R. Montoya-Torres, A. Jaegler, "Sustainable supply chain network design: a study of the Colombian dairy sector", *Annals of Operations Research*. Submitted (2nd rev.)	Journal paper (submitted, under second review)	JCR: Q2 Scopus: Q1	Ch. 4
C.A. Moreno-Camacho, A. Jaegler, J.R. Montoya-Torres, N. Gondran, "Agrifood Supply Chain Network Design Under Sustainable Development Policies". *European Journal of Operational Research*. Submitted	Journal paper (submitted)	JCR: Q1 Scopus: Q1	Ch. 5, 6, 7
C.A. Moreno-Camacho, J.R. Montoya-Torres, A. Jaegler, "Designing a Sustainable Supply Chain", *Studies in Computational Intelligence*, vol 853, pp. 15-26. (In: Borangiu T., Trentesaux D., Leitão P., Giret Boggino A., Botti V. (eds) *Service Oriented, Holonic and Multi-agent Manufacturing Systems for Industry of the Future. SOHOMA 2019*)	Book chapter of conference proceedings	Scopus: Q4	Ch. 3
C.A. Moreno-Camacho, J.R. Montoya-Torres, A. Jaegler, N. Gondran, "Identifying sustainability metrics at real applications of the Supply Chain Network Design problem: A systematic Literature review", *Conference on Sustainability Science 2018: Ecology and Sustainability Science from Theory to Practice*, Java, Indonesia	Conference presentation	n.a.	Ch. 2

Table 1.1. Publication outputs of this research (continued)

Reference	**Publication type**	**Indexed**	**Related chapter**
C.A. Moreno-Camacho, J.R. Montoya-Torres, A. Jaegler, N. Gondran, "Sustainable Supply Chain Network Design in the Dairy Industry", *9th International Workshop on Advances in Cleaner Production,* (On line), Melbourne, Australia	On-line Workshop Proceedings-Book	n.a.	Ch. 6
C.A. Moreno-Camacho, J.R. Montoya-Torres, A. Jaegler, N. Gondran, "Evaluating economic, environmental and social criteria in supply chain network design", *XXIII Ibero Latin America Summer School of Operational Research (ELAVIO'19)*, Lleida, Spain.	Poster at doctoral school	n.a.	Ch. 3

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Chapter 2 Literature Review

Partial content of this chapter is published in Moreno-Camacho, C. A., Montoya-Torres, J. R., Jaegler, A., & Gondran, N. (2019). Sustainability metrics for real case applications of the supply chain network design problem: A systematic literature review. Journal of Cleaner Production, 231, 600–618. https://doi.org/10.1016/j.jclepro.2019.05.278

The current chapter presents a review of academic literature related to sustainable supply chain network design (SSCND). It includes a review of modeling strategies and solution methods for decision making when the three pilar of sustainability, or at least two of them, are considered in order to define the location of facilities within a supply network (e.g., economy and environment). Besides, it presents a report of metrics and sustainability assessment tools included in analytical methods for supply chain design. Considering the object of study of the present work, a particular emphasis is placed on reviewing methodologies for measuring sustainability in the agricultural sector. Figure 2.1 presents an overview of the content of the chapter.

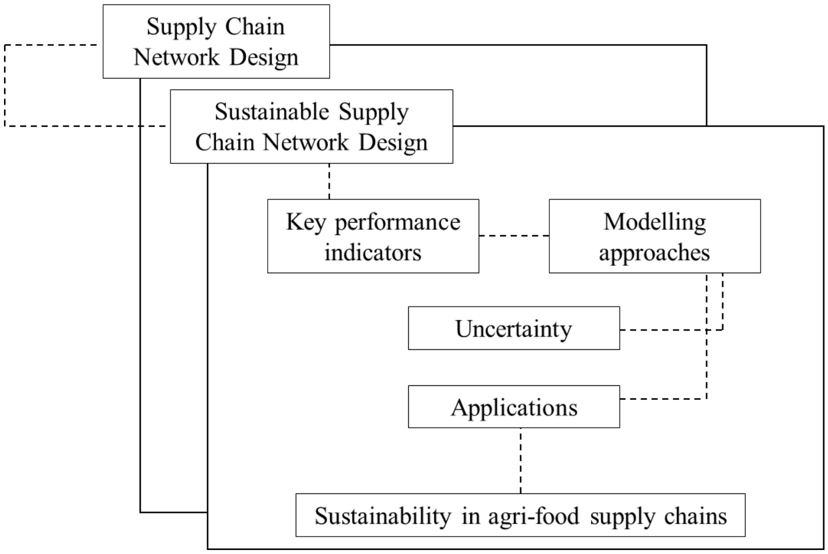


Figure 2.1. Overview of the chapter

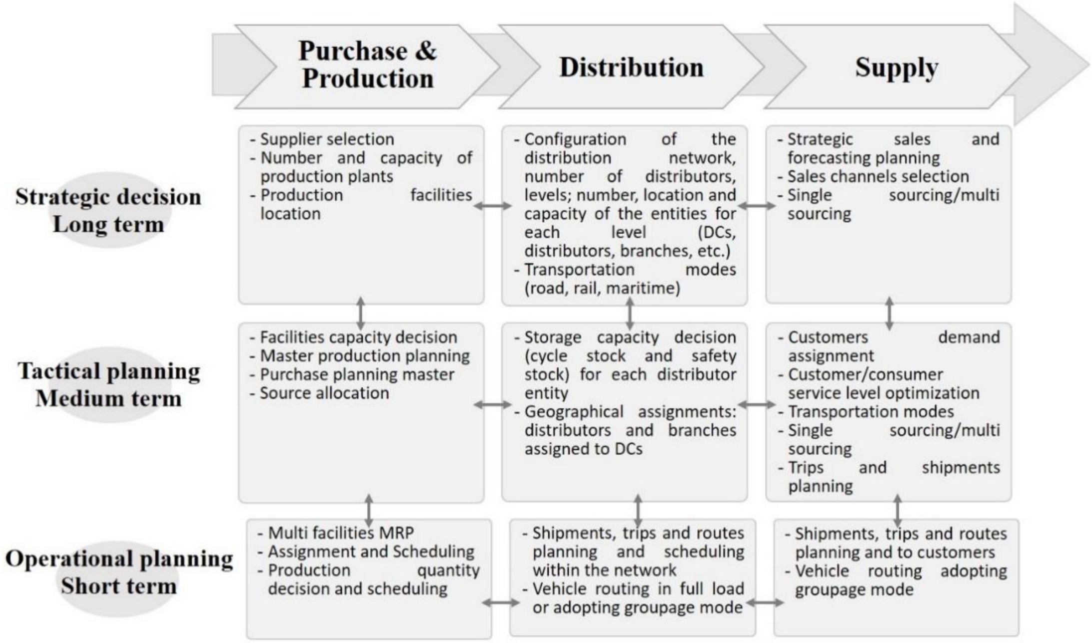
1. Supply chain network design

Supply chain network design (SCND) encompasses multiple decisions at the tactical and strategic levels in the supply chain management context. Indeed, as is stated by (Eskandarpour et al., 2015; Pourhejazy & Kwon, 2016), different disciplines such as management, logistics, and Operations Research are interrelated with in this topic, which presents a challenge to consolidate and synthesize a definition for the field. Figure

2.2 presents a framework of the problems addressed within the SCND field at different decision levels and corresponding with different activities in the supply chain.

In the scientific literature, SCND is often understood as part of the supply chain planning process at the strategic level. Mainly, decisions aiming to shape the structure of the distribution network, such as determining the number of tiers, the number of facilities at each tier, their geographical location, their capacity, and technology, as well as determining the flow of material from one location to another. According to (Govindan et al., 2017; Mangiaracina et al., 2015), SCND also comprises the definition of strategic policies concerning inventory and transportation modes. Indeed, during the last decades, SCND has been one of the most active application fields of Operation Research and the Management Sciences (Barbosa-Povoa et al., 2018; Calleja et al., 2018; Garcia & You, 2015). Even though the design of an entirely new network is not very frequent, the redesign of existent supply chains, as a consequence of political decisions, new suppliers, and new technologies, pose the same challenges.

Usually, in the classical literature of Supply Chain Management (SCM), the problem of determining the structure of the network of a supply chain is addressed from an economic perspective. Models frequently establish the minimum total operational cost as a decision criterion; meanwhile, the objective of profit maximization has received less attention (Mangiaracina et al., 2015). However, over the last few years, with the growing global concern about environmental and social impacts derived from supply chain operations, both practitioners and academics have seen the need to incorporate additional factors allowing a broader assessment of the supply chain in the three dimensions of sustainability.



	Purchase & Production	Distribution	Supply
Strategic decision Long term	- Supplier selection - Number and capacity of production plants - Production facilities location	- Configuration of the distribution network, number of distributors, levels; number, location and capacity of the entities for each level (DCs, distributors, branches, etc.) - Transportation modes (road, rail, maritime)	- Strategic sales and forecasting planning - Sales channels selection - Single sourcing/multi sourcing
Tactical planning Medium term	- Facilities capacity decision - Master production planning - Purchase planning master - Source allocation	- Storage capacity decision (cycle stock and safety stock) for each distributor entity - Geographical assignments: distributors and branches assigned to DCs	- Customers demand assignment - Customer/consumer service level optimization - Transportation modes - Single sourcing/multi sourcing - Trips and shipments planning
Operational planning Short term	- Multi facilities MRP - Assignment and Scheduling - Production quantity decision and scheduling	- Shipments, trips and routes planning and scheduling within the network - Vehicle routing in full load or adopting groupage mode	- Shipments, trips and routes planning and to customers - Vehicle routing adopting groupage mode

Figure 2.2. Supply chain network design activities by decision level
(Manzini et al., 2011)

In fact, during the last decades, the integration of the triple-bottom-line (TBL) dimension in classical Operations Management problems has attracted an increasing number of researchers and practitioners, making sustainability one of the most active supply chain management topics. This fact is reflected by the growing number of original papers addressing this issue like in (Ansari & Kant, 2017; Gupta & Palsule-Desai, 2011; Rajeev et al., 2017; Seuring & Müller, 2008; Touboulic & Walker, 2015) and also, by the increasing number of review papers aiming to synthesize the progress in the area (Ansari & Kant, 2017; Carter & Washispack, 2018; Rajeev et al., 2017).

2. Sustainable supply Chain Network Design

During the last three decades, the problem of designing sustainable supply chains has become an issue of growing interest to the scientific community, which is reflected in the number of published articles related to the subject (Eskandarpour et al., 2015; Moreno-Camacho et al., 2019). Classical operation research cost-driven models were extended to consider environmental factors in objectives, constraints, or parameters, in relation with the involved decisions (i.e., facility location, transport mode selection, technology selection, among others), making ways to what is known as Green Supply Chain Network Design (GSCND) (Eskandarpour et al., 2017; Xu et al., 2019). Eskandarpour, Dejax, Miemczyk, & Péton (2015), present a comprehensive literature review, analyzing 87 papers, published from 1990 to 2014, addressing the design of sustainable supply chains, with particular emphasis on the optimization methods used to solve the problem. Noteworthy, about 70% of the reviewed papers were published after 2009. That review highlights the way in which environmental assessment has progressively gone from partial evaluation of environmental impacts from one or more operations in supply chain (i.e., manufacturing, inventory, transportation, etc.) to a more comprehensive methodologies like carbon footprint and life cycle assessment (LCA) and its inclusion in classical optimization techniques from the field of Operations Research. As stated by (Blass & Corbett, 2018), there is a potential to build bridges between the industrial ecology and the Operation Management / Research communities, while the latter increasingly converge around sustainable supply chains.

On the other hand, previous reviews on sustainable supply chain design also mention how factors assessing the performance of the supply chain on the social dimension has been included in a less extent (Bubicz et al., 2019; Eskandarpour et al., 2015; Moreno-Camacho et al., 2019). Certainly, corporate social responsibility performance is one of the essential assessment challenges in the context of supply chain, however, it is occasionally misinterpreted. Sometimes, corporate social responsibility is linked with the fact of companies spending great amount of money in charity or other sort of philanthropic activities, but in accordance with Grant, D. B., Trautrims, A., and Wong (2017), this is not necessarily related. In fact Carroll (1979), affirms that corporate social responsibility integrates four not mutually exclusive categories, namely, economic, legal, ethical, and discretionary responsibilities of business to society. These categories are useful to conceptualize the key issues in social performance. First, companies are called to be profitable as the basic economic unit in the society. Second, it is expected of companies to operate within the framework of legal requirements and regulations. The third category encompasses for additional ethical behaviors on companies, which are above law, but nevertheless are expected by the society. Finally, voluntary activities in which companies assume a role of helping society, which not imperative, nor legally imposed, nor generally expected in an ethical sense either.

From a quantitative point of view, the aforementioned presents a significant challenge to the evaluation of social performance in the supply chain context, in particular, at the long-term level where supply chain network decisions are framed. Although some economic and environmental criteria can be modeled as a cost function (e.g., carbon footprint emissions, production, and transportation costs, etc.), some environmental and social issues cannot be represented merely as a cost or flow function. Indeed, some crucial issues are qualitatively defined (e.g., public responsibility, respect of human rights, etc.) and may not be transformed as a quantitative function. Not surprisingly, the complexity of representing social conditions through numerical indicators, the lack of consensus on the accurate criteria for its evaluation, the lack of appropriate methods to measure social performance at supply chain level, and the scarcity of available data are the most relevant reasons for the late development of social assessment (Bubicz et al., 2019; Eriksson & Svensson, 2015; Popovic et al., 2018).

Nevertheless, there is an increasing concern of evaluating social impacts to harmonize practices ensuring social equity, ecosystems protection, and economic development as is reflected on recent publications (Messmann et al., 2020). As the concern for developing and managing sustainable supply chains grows, indicators and assessment tools for social and environmental performance acquire great prominence. The following section presents an extensive review on sustainability indicators in strategic supply chain optimization.

3. Sustainability indicators for supply chain optimization

Considering the growing interest in involving environmental and social factors into analytical decision-making models at supply chain context, there are at least two elements worth to highlight. On the one hand, sustainability indicators depend heavily on available data and their possibility of being represented as an element of the model. On the other hand, sustainability assessment tools offer a methodology to quantify or assess these indicators. The current subsection presents a review of the most common sustainability indicators in supply chain network design formulations.

Sustainability has a measurable character in the supply chain context that matches the concepts of efficiency and effectiveness. It involves that sustainability is not just an external standard to satisfy requirements from stakeholders (effectivity). It must also consider internal standard accomplishment to ensure the profitability and continuity of business (efficiency). Sustainability addresses the balance of economic, environmental and social objectives. According to Taticchi, Tonelli, & Pasqualino (2013), the notion of balance in performance measurements of sustainability implies the necessity of using different metrics and perspectives that tied together provide a holistic view of the organization. Hence, the use of metrics constitutes an important element to determine efficiency and effectiveness and letting to compare between competing alternative solutions (Dekker et al., 2012; Hervani et al., 2005).

Additionally, the sustainability term presupposes a behavior that reaches a steady state wherein established parameters for each dimension of sustainability (i.e., economic, environmental, and social) can be kept in the long term (Kannegiesser & Günther, 2014). It is not by coincidence that academics have become increasingly interested in sustainability assessment regarding decisions at the strategic level of the supply chain. Indeed, these decisions have considerable impacts in the long-term, and define action boundaries in the tactical and operational decision levels (Barbosa-Póvoa et al., 2018).

According to Stindt, Sahamie, Nuss, & Tuma (2016), assessing sustainability in the supply chain field requires multidisciplinary teams, as the approach extends beyond economic consideration to include ecological and social factors, which the management researchers are often unfamiliar with. In this sense transdisciplinary research is encouraged, however, the integration between SCM models and social and environmental sciences is weak, affecting the quality of the proposed models. The operations research (OR) methods commonly used to address problems in SCND can often be criticized for their shortcomings in fieldwork (Stindt et al., 2016). In some cases, the selection of the metrics is too generic and does not response to the challenges faced by the specific industry under study; in the economic, environmental, or social dimensions. This leads to a lack of holistic understanding and shortcomings in the abstraction and its consequent modeling of real-world problems (Stindt, 2017). Hence, the usefulness of these works as support for decision making in real applications is often compromised.

Results presented in this section are part of the review paper published in (Moreno-Camacho et al., 2019). The review was intended to respond to the following questions:

i. What are the common economic, environmental, and social criteria considered in applied cases of design or redesign of supply chain networks?
ii. What solution methods are employed to deal with the problem?
iii. What real cases are described in the scientific literature?

The work uses an existent framework proposed by Chardine-Baumann & Botta-Genoulaz (2014) to classify sustainability assessment indicators for supply chain network design. Figure 2.3 presents the model composed of fifteen sustainable fields, five fields for each dimension (i.e., economy, environment, and society), each of them is linked to one of the main challenges faces for companies to reach sustainability. A total of 113 papers were considered in the analysis and the results are presented below.

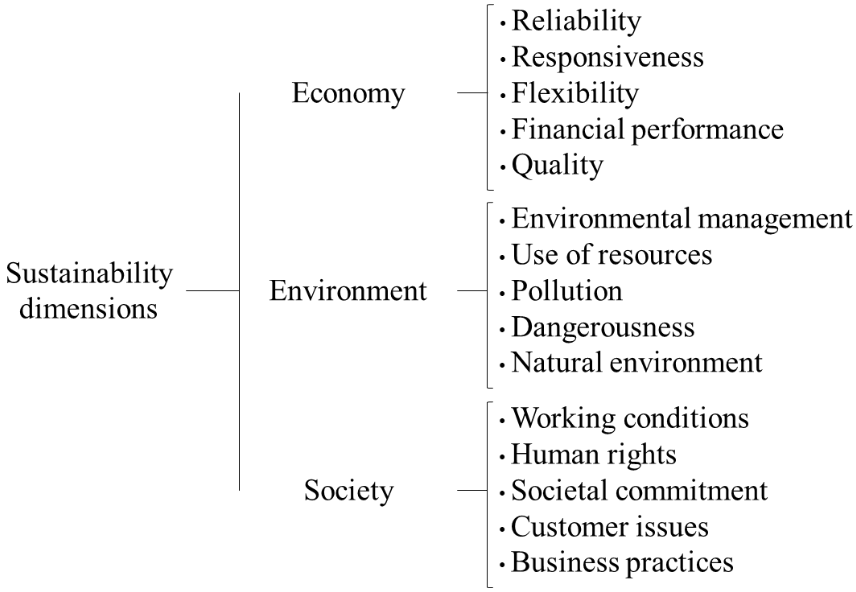


Figure 2.3. Classification scheme for sustainability indicators (Chardine-Baumann & Botta-Genoulaz, 2014)

3.1. **Economic indicators**

From the review of the studies, it can be concluded that the evaluation of the economic dimension focuses primarily on the *financial performance* category. Although this dimension attends for several different fields, other fields such as reliability, responsiveness and flexibility has received little attention.

Three main indicators appear to be related to the economic dimension: minimization of total cost, maximization of profit (MP), and maximization of net present value (NPV). The last is common when the problem considers an evaluation over multiple time periods, while the first two appear in both multiple and single periods evaluation. This condition is not a minor detail as the sustainability may be not seen as a stationary assessment in one point of time but as a kept state over time.

In line with decisions in the design of the supply network, facility location, and transportation cost are the most common components of the cost. These cost drivers appear in 62% and 53% of the reviewed papers, respectively. Other drivers of the cost include production, purchasing and holding costs, with 41%, 37% y 26%, respectively. About 16% of the studies include fix and variable operational costs, while the cost caused by carbon emissions is present in about 12% of the works. Taxation over carbon emissions is one of the worldwide initiatives aiming at reducing GHG emissions in both developed and developing countries by encouraging the investment on cleaner technologies (Xu, Pokharel, et al., 2017). The most usual carbon policies include carbon cap, carbon emission tax and carbon cap and trade (Jin et al., 2014). The carbon cap policy has not a direct affection over the cost since it determines a threshold over the number of allowable emissions to a company. Meanwhile, carbon tax emissions and carbon cap and trade, enact a relation of substitution between economic and environmental resources.

Figure 2.4 presents a summary of the relative frequency of use of the set of cost drivers identified during the review.

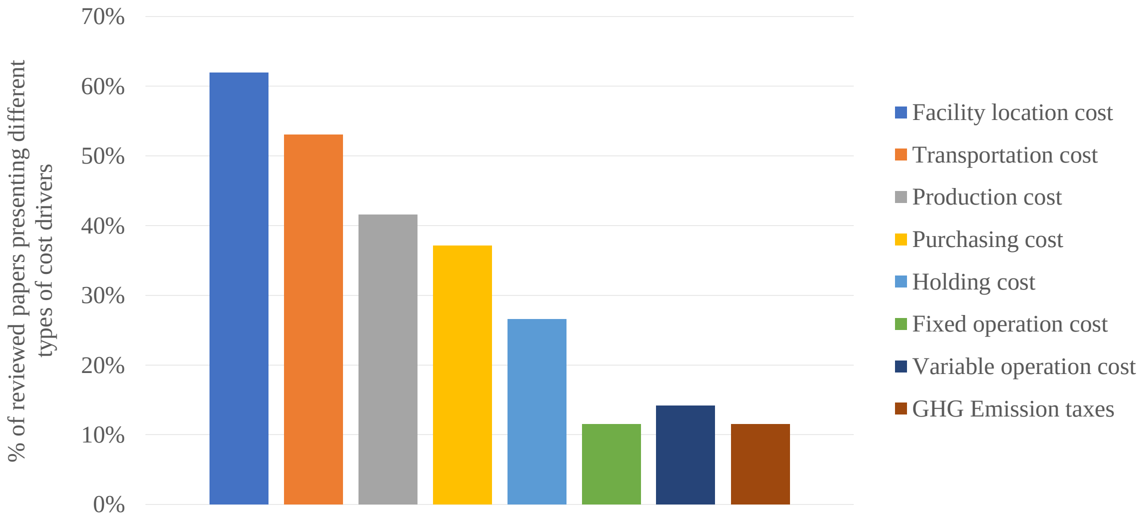


Figure 2.4. Relative frequency of use of cost drivers (Moreno-Camacho et al., 2019)

Notably, from the 13 papers covering carbon cost, only Rezaee, Dehghanian, Fahimnia, & Beamon, (2017) state an existing relation; not necessarily linear, but positive between the green design of the chain and both carbon price and budget availability. This conclusion might open new ways in the design of effective policies for reducing emissions and consumption of natural resources.

3.2. **Environmental indicators**

Life cycle assessment (LCA) methodologies offer a complete approach to the evaluation of environmental impacts through the whole supply chain, however, sometimes due to methodological, technical, or informative barriers an LCA analysis is not possible or would be to costly. Indeed, most of the works opt for partial evaluation considering the more challenging activities in the supply chains.

An analysis of the assessment of environmental performance within the five fields listed in the used framework is presented below. The *Environmental management* field evaluates the impacts derived from the environmental certification owned by the company, in compliance with the environmental regulation within a specific sector, as well as the number of resources invested in environmental protection. The last one is readily convertible into a cost driver, while the others correspond to a qualitative measure, seldom included into the SCND problem, but broadly evaluated within the partner selection problem.

One of the most significant impacts caused by the company operations comes from the use of raw or recycled material, water and energy in the surrounding area, those factors are grouped in the *use of resources* field. For instance, Feitó-Cespón et al. (2017) consider the environmental impact of using waste material instead of virgin raw material in a plastic recycling supply chain.

Water consumption appears frequently (for example in Anvari & Turkay(2017), Awad-Nunez, Gonzalez-Cancelas, Soler-Flores, & Camarero-Orive (2015), Clavijo Buritica & Escobar (2017) and Varsei). Christ, & Burritt (2017) deal with the availability of water issue at the candidate location. Anvari & Turkay (2017) also evaluate the consumption in the pre-operational stage of facilities (i.e., during the facility construction process). Meanwhile, the amount of water used into the production process is an important issue consider in Fahimnia & Jabbarzadeh (2016), Feitó-Cespón et al. (2017), Jafari, Seifbarghy, & Omidvari, (2017) and Miranda-Ackerman et al. (2017). The last one highligthes the relationship with the adopted process technology.

Energy consumption from production process is also considered often as in Azadeh et al. (2017), or from warehouses activities in Colicchia et al. (2016). Miranda-Ackerman et al. (2017) considers energy consumption depending of the selection of processing technology. Zhalechian et al. (2016) consider the waste of energy derived of waiting time for vehicles to be unloaded at collection centers in a reverse supply chain. Accorsi et al. (2016) address the design of an agri-food supply chain in which the total amount of energy used in transport and production would be smaller than the amount of energy produced by renewable sources such as solar fields or wind farms in an agri-food supply chain.

The *pollution* field has been broadly covered, especially for the air pollution sub-field. Although, there are multiple sources of contamination along the supply chain, our review shows that, most of the works focus on GHG emissions assessment at *Scope 1* or Scope *2*. As defined by the Greenhouse Gas (GHG) Protocol. *Scope 1* embodies direct emissions from owned or controlled sources (e.g., company vehicles and company facilities). *Scope 2* comprehends indirect emissions from the generation of purchased electricity, steam, heating, and cooling consumed by the company. Finally, *Scope 3* includes all others indirect emissions that occur in the supply chain the company belongs to. Figure 2.5 presents a graphic view of the sources of emissions included at every scope.

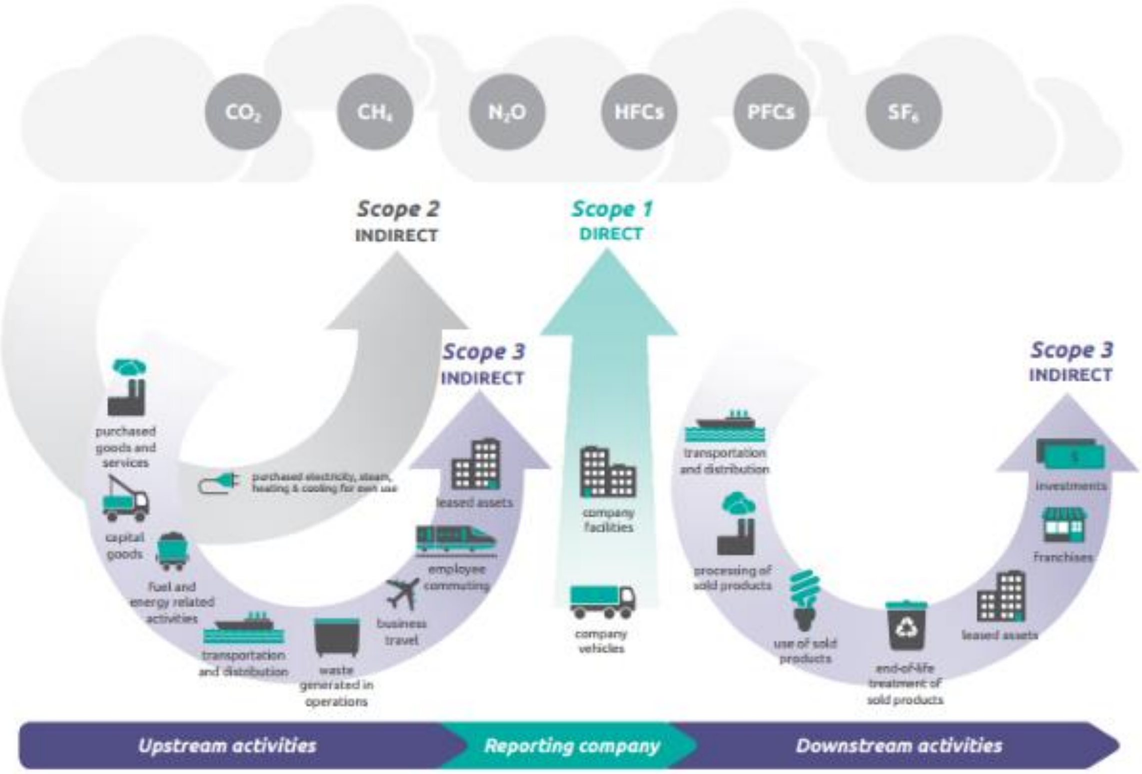


Figure 2.5. GHG emissions scopes
Source: Greenhouse Gas Protocol

Hence, CO_2 emissions from transportation activities and facilities operation are the more frequent sources, considered in real cases. This is not surprising, since transport sector, including the movement of people and goods produces around 20% of global energy-related CO_2 emissions, approximately 80% of them originating from road transportation (Sims et al., 2014). Contribution of CO_2 emissions for transportation activities are generally expressed as a product of the distance and the emission factor of fuel consumption. More sophisticated methodologies to calculate CO_2 emissions for transportation activities are possible but unconventional on the papers dealing with the SCND problem. Rajkumar & Satheesh Kumar (2015), calculate CO_2 emissions as a function of the capacity in weight used of the truck transporting the product between the different echelons. Additionally, in (C. Chen et al., 2017), the authors include factors affecting the vehicle emissions depending on vehicle type and shape, road conditions and regional climate. A sensibility analysis let them conclude about the importance of road conditions over environmental impact what might result in a critical point for establishing sustainable supply chains in some developing countries suffering from lack of appropriate highways for both freight transportation and passenger transportation.

Operation of industrial facilities is the second most-common factor used to measure environmental impact in the supply chain design. In accordance with (Sims et al., 2014), facilities operation also contributes to about 28% of global energy-related GHG emissions and is therefore a significant factor. At industrial facilities, GHG direct emissions come mainly from production process involving combustion of fossil fuel for power or heat. GHG indirect emissions are the result of energy consumption of power industrial buildings and equipment. Emissions from industrial facilities deteriorate air quality with several polluting compounds. Several types of atmospheric pollutions can be observed, for example:

- Photochemical air pollution, for instance, is related to the emissions of different types of gas such as VOC or NOx, that interact with the oxygen of the air to produce ozone, which is a strongly reactive and it is the cause of several health issues, such as asthma.
- The release of sulphuric or nitrous oxides may generate acid rains.
- The release of CFC gases contributes to the erosion of the ozone layer.
- The release of greenhouse gases (GHG) contributes to climate change, which is today one of the most studied issues of air pollution

According to (Fischedick et al., 2014) more than 80% of total emissions correspond to CO2, about 8% to methane, other compounds including hydrofluorocarbons, perfluorocarbons, nitrous oxide and Sulphur hexafluoride constitute the remaining approximate 10% percentage. Global warming potential values relatives to CO_2 permit to convert emissions of different compounds into equivalent CO_2 units (CO_2 eq.) to standardize the unit of measure.

The most common factor to quantify the environmental impact of industrial facilities is direct emissions from manufacturing process. Some authors also consider emissions from others buildings such as warehouses, recollection centers, dismantling centers, and so on in (Aalirezaei & Shokouhyar, 2017; Brandenburg, 2015; Ghaderi et al., 2018; Govindan et al., 2015; Govindan, Jha, et al., 2016). Carbon footprint, as defined by Wiedmann & Minx, (2008), as the total amount of carbon emissions that is directly and indirectly caused by an activity is less extended and addressed, among others by (Accorsi et al., 2016; Azadeh et al., 2017). Furthermore, as an own feature of the SCND problem, some studies consider not just emissions at the operational phase but also the emission caused during the construction process or pre-operational phase, air pollution as a result of construction of facilities is considered in Anvari & Turkay (2017) and Arampantzi & Minis (2017).

Pollutant emissions related to materials are studied in (Zhou et al., 2017). In this work, a computer manufacturing company has the possibility to choose between different modules to assemble a piece of equipment. The purchase decision is supposed to be characterized not only by the difference in the cost of the different modules but also by the amount of emissions derived from the product during the assembly stage and during its useful life.

Pollution caused by raw materials acquisition or use of final products are less frequently studied (Kannegiesser et al., 2014). Additionally, since most of the studies focus on a single company rather than a holistic view of the sector, GHG emissions generated by suppliers is fewer considered. Figure 2.6 presents the number of studies considering GHG emissions using partial assessment.

Additionally, water pollution and land pollution are scarcely studied in real applications of the SCND problem. Anvari & Turkay (2017) consider this factor in relation with the waste generated during construction of the facilities, they consider a sensitive waste factor to the location due to a location with a higher population, and higher aquifers level are more sensitive to waste. Chávez et al. (2018) evaluate the positive effect of using agricultural waste from coffee crops to produce biofuel avoiding dumping these wastes into the water sources. Besides, other types of pollution like noise, smells, visual pollution, vibrations, and radiations do not take part in the environmental impact assessment of the design of supply chains.

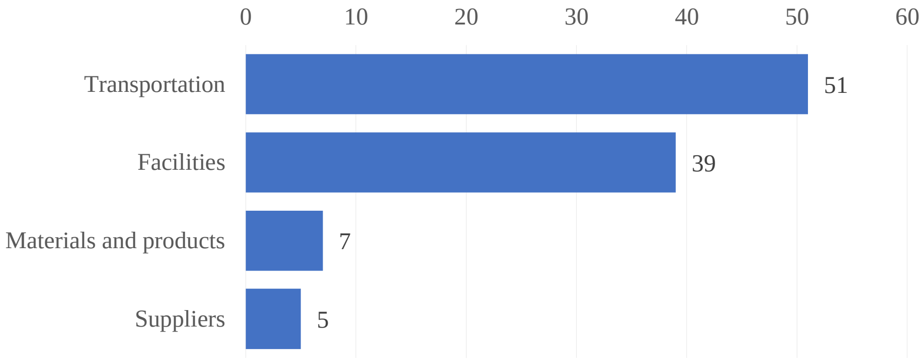


Figure 2.6. Driver factor for GHG emissions environmental impact assessment (Moreno-Camacho et al., 2019)

Finally, no papers were found attending to the consideration in the *Dangerousness* field. Meanwhile, in the last field *Natural environment*, just two papers include considerations over promotion and protection of biodiversity. Accorsi et al. (2016), consider the use of land in a rural region, including a reforestation activity. The authors calculate the number of hectares of land devoted to planting trees, in such a way that ensure a zero-carbon emissions operation in a food supply chain, emissions associated with cultivation and logistics activities must be equated to emissions captured by the forest. Izadikhah & Saen (2016), consider a biodiversity factor, calculated like the loss of species caused by building a new facility in the candidate zone.

3.3. **Social indicators**

The current section presents the findings regarding the different categories in the social dimension . In the sub-field *work conditions*, employment is the most frequent social indicator used in at measuring social performance at supply chain level. The total number of jobs created is considered by most authors, with small adjustments. Miret et al., (2016), evaluate the social benefit of the total number of created jobs. They use an approach to estimate not only the direct jobs created in the transformation echelon but also the indirect and induced jobs created through the whole set of activities in the life cycle of the product. Anvari & Turkay, (2017), Arampantzi & Minis (2017), Ghaderi et al., (2018), Varsei & Polyakovskiy (2017), Zahiri et al. (2017), Zhalechian et al. (2016) and X. Zhu, Wang, & Tang (2017) consider creating jobs with priority in regions with the highest unemployment rate. Argument here is that the same number of job opportunities will cause greater social impact in areas with higher rates of unemployment that in more prosper regions. Mota et al. (2018) also consider the number of jobs created by transportation activities with different transport mode. Employment due to the construction of new facilities is addressed in Osmani & Zhang (2017), Roni, Eksioglu, Cafferty, & Jacobson (2017) and Mousavi Ahranjani et al., (2018).

Another factor considered in the *working condition* field is health and safety of employees. As an example, Ghaderi et al. (2018) uses the total number of lost days by year caused by injuries to establish an indicator for employee’s health, the number of occurred injuries during a period time is related to the selection of technology at each facility. Aalirezaei & Shokouhyar (2017) addressing the design of a reverse supply chain for waste from electrical and electronic equipment, introduce a parameter quantifying the damage caused to workers at the collection centers, due to the exposition to hazardous substances. Other aspects related to working conditions as employee satisfaction and stability are addressed in (Arampantzi & Minis, 2017). The authors study both idle time and dismissals to serve as indicators.

Regarding *societal commitment*, the main factor that is considered is wealth creation and social progress within host countries, by increasing their gross domestic product (GDP). In this case, regions with lower economic development have priority for the location of new facilities. This condition is considered in (Anvari & Turkay, 2017; Arampantzi & Minis, 2017; Babazadeh, Razmi, Rabbani, & Pishvaee, 2017; Ghaderi et al., 2018; Mota, Carvalho, Gomes, Barbosa-Povoa, et al., 2015; Varsei & Polyakovskiy, 2017; Zahiri et al., 2017 and Zhalechian et al., 2016). According to Anvari & Turkay (2017), this consideration promotes fair distribution of development through the regions and, along with creating jobs in regions with higher unemployment rates, helps reduce immigration and its potential consequences. However, location in less developed areas considerably affects environmental and economic objectives due to the increase in the distance between production and consumer sites, the lack of environmental and social regulation, and the scarcity of skilled workforce.

Regarding the same field, Anvari & Turkay (2017) introduce other conditions affecting community development such as security level, medical facility access, and educational level at facility location region. Security at the location is crucial for the operations of the company and the habitat of the employees. Besides, access to medical services and education offers workers and their families favorable conditions for settling in the area and provides the company with the opportunity to find skilled workers and deal with staff turnover.

The field *customer issues* groups together all the actions carried out by the company and the effects they have on the consumer. For instance, since some products may have health impacts on consumers, companies are responsible for providing safe products. That condition is considered by Ghaderi et al. (2018) and L. Zhu & Hu (2017). The authors consider the number of hazardous products going out of the production line based on the production technology. Besides, in some works, demand satisfaction is used as an indicator of social performance because the deprivation of some products could impact the consumer. This condition is evaluated in Anvari & Turkay (2017), Ashfari, Sharifi, ElMekkawy, and Peng (2014), and Feitó-Cespón et al. (2017). Y. Zhang et al. (2016) use a similar approach in a reverse supply chain for recovering waste cooking oil in China. Authors argue that to satisfy the demand helps to reduce the illegal trade of edible oil in this country, representing a tremendous social benefit.

Inclusion of sustainability factors in the design of supply chains deals with the evaluation of new criteria and essentially it works with the existence of conflicting objectives. The academic literature presents several modeling approaches and solution techniques to deal with the evaluation of environmental and social criteria into the SCND. These models are usually based on classical location-allocation facilities models to which are added, either new objectives or additional constraints to address the assessment of performance of environmental and social dimensions. A description of these approaches is presented in the following section.

4. Sustainable supply chain design modeling approaches

From an Operations Research perspective, SCND comprises the definition of optimal location and capacity of the facilities at each level of the network, it also allows to define the flow of materials among facilities. The use of mathematical programming-based methodologies is widespread.

4.1. Single objective formulations

This type of formulation usually considers an economical objective and defines constraints to the fulfillment of the defined sustainability criteria. This approach enriches the conventional SCND model by adding constraints for the social and the environmental dimension. For instance, declaring a cap in the total amount of GHG emissions or defining a minimum number of created jobs. This approach keeps the focus on logistics operations in the supply chain, while integrating new concerns into the decision process Eskandarpour et al. (2015).

Frequently, under this modeling approach, environmental impacts caused through the chain are monetized under a carbon-taxes schemes. Taxation over carbon emissions is one of the worldwide initiatives aiming at reducing GHG emissions in both developed and developing countries (Xu, Pokharel, et al., 2017). The most usual carbon policies include carbon cap, carbon emission tax and carbon cap and trade (Jin et al., 2014). On the one hand, a carbon cap policy has not a direct impact over the cost since, it determines a threshold over the number of allowable emissions to a company. In terms of the model, it is expressed as an additional constraint. On the other hand, carbon tax emissions and carbon cap and trade schemes, enact a relation of substitution between economic and environmental resources. In this case the emission cost is an additional driven for the total cost.

As an example, Almansoori & Betancourt-Torcat (2016) address the design of a hydrogen supply chain network considering both carbon emission cap and carbon emission taxes as a strategy to promote CO_2 emissions reductions. Xu, Elomri, et al. (2017) work in the design of a reverse supply chain for solid waste recycling considering a carbon emission cap. Accorsi et al. (2016) propose a single objective model considering a zero-carbon supply chain for the design of a regional potato supply chain. The model ensures that total emission caused by crop and logistics activities in the food supply chain are offset by tree planting and its potential for carbon sequestration. Quddus et al. (2017) include a carbon trading mechanism that allow decision makers to sell or buy carbon credits while monitoring emissions from supply chain. D. Zhang et al. (2017) and Zhou et al. (2017) present an analysis on the structure of a supply chain considering different tariffs on carbon taxes. The authors conclude that carbon tax ratio influences the structure of the supply chain and the allocation of demand as well.

4.2. Multi-objective formulations

A second optimization strategy to deal with sustainability assessment in SCND is *Multi-objective optimization* (MOO). Under this approach, it is assumed the existence of multiple conflicting sustainability objectives. Generally, the model contains one objective for each evaluated dimension of sustainability. Broadly speaking, economic objectives consist of a summation of cost from strategical and tactical decisions. Environmental objectives quantify the environmental impact in the network; in some cases, it is expressed like sums of the equivalent CO_2 emissions generated from production and transportation activities when a partial scope evaluation is considered. Other works using LCA-based approach consider the sum of environmental impacts through the entire product life cycle to construct an environmental objective function.

Additionally, since social assessment might involves several factors with different measurement units, objective functions for the social dimension are frequently constructed as a linear weighting of the deviation from optimal value of each factor assessed as in Anvari & Turkay (2017) and Zahiri et al. (2017). As an example (Zahiri et al., 2017) consider two social objectives in only one objective function. It evaluates total created job opportunities and economic development at the same time. The use of this sort of compound criteria might lead to overcompensation among the factors. The poor performance of one factor is masked by the outstanding performance of another factor.

Depending on the solution approach either *a priori* or *a posteriori* method can be utilized. Regarding *a posteriori* methods, both exact and heuristic methods are utilized to define the set of non-dominated solutions that represent the set of “optimal” candidate solutions (Marler & Arora, 2004). The most widely used generation methods remain the weighted metric method as in Afshari et al. (2016), C. Chen et al. (2017) Colicchia et al. (2016) and Govindan, Jha, et al. (2016) and the ε-constraint method as in Anvari & Turkay (2017), Arampantzi & Minis (2017), Feitó-Cespón et al. (2017) and Varsei & Polyakovskiy, (2017). Evolutionary algorithms for multi-objective optimization appears in Afshari et al. (2016), Azadeh et al. (2017) and Miranda-Ackerman et al. (2017). Hence, the decision maker is provided with a set of equally optimal solutions to select from them the one what best suits.

4.3. Time to sustainability formulation

Finally, one of the most recently developed strategies to deal with sustainability assessment within the SCND context is the *Time to sustainability* (TTS) approach. It might be defined as a single objective formulation, however, unlike the previous formulation the main objective does not account for money but for time. In this regard the model accounts for the number of periods of time (e.g., years) until every sustainability indicator reaches an acceptable pre-defined value. This approach was firstly introduced in (Kannegiesser & Günther, 2014), where an application for the European automotive sector is presented (Kannegiesser et al., 2014).

TTS optimization strategy overcomes the drawback of multi-objective optimization models since the weighting of objectives is not required. It means that the decision maker is not faced with defining relative preferences of conflicting objectives. Furthermore, considering the time dimension confers to sustainability a dynamic character, based on the observation that in the long-term, conflicting objectives often reach an acceptable steady state due to technological advances and regulations of external conditions. Variants of the TTS approach are presented in (Kannegiesser et al., 2015). These new variants overperform the basic TTS approach previously mentioned in respect to the validity of results and the computational time. To the best of our knowledge, the TTS optimization strategy has been scarcely studied into the academic literature despite its advantages, originality, relevance and flexibility to deal with several different sustainability metrics in parallel.

4.4. Deterministic and non-deterministic considerations

In real scenarios of the supply chain, decisions are rarely made under certainty. Moreover, since SCND problem implies long-term decisions, there are multiples parameters that might change across the time. Several works in the literature incorporate uncertainty into their modeling approach. We found demand to be the most common uncertain parameter considered 13 papers out of 77 address it. Five works consider uncertainty in supply: including papers considering uncertainty in harvest rate for biofuel conversion. Uncertainty on recycled products rate as the number of units recovered from the market in a closed-loop supply chain scenario is addressed in four papers. Finally, other non-deterministic parameters included corresponding to production and transportation costs and facilities capacity. Table 2.1 presents a list of some recent works addressing sustainable supply chain design classified by modeling characteristics.

Table 2.1. Modeling approaches for SSCND

Modeling approach		**Reference**
Single objective		
	Deterministic	***Eco + Env***
		(Accorsi et al., 2016; Almansoori & Betancourt-Torcat, 2016; Babazadeh, 2018; Clavijo Buritica et al., 2017; Costa et al., 2018; Duarte et al., 2016; Galvez et al., 2015; Izadikhah & Saen, 2016; Mohd Idris et al., 2018; Varsei et al., 2017; D. Zhang et al., 2017; Zhou et al., 2017; Zohal & Soleimani, 2016)
		Eco + Soc
		(Babazadeh, Razmi, Rabbani, et al., 2017)
	Stochastic	***Eco + Env***
		(Ahn & Han, 2018; Fahimnia et al., 2018; Ghelichi et al., 2018; Quddus et al., 2017; Rezaee et al., 2017; Saif & Elhedhli, 2016; Xu, Elomri, et al., 2017)
Multiple objectives		
	Deterministic	***Eco + Env***
		(Cambero et al., 2016; C. Chen et al., 2017, 2018; Y. W. Chen et al., 2017; Colicchia et al., 2016; Domínguez-García et al., 2017; Fang et al., 2018; Gao & You, 2015; Govindan, Garg, et al., 2016; Kuo et al., 2017; Miranda-Ackerman et al., 2017; Murillo-Alvarado et al., 2015; Nodooshan et al., 2018; Palacio et al., 2015; Tang et al., 2016; Urata et al., 2017)
		Eco + Env + Soc
		(Aalirezaei & Shokouhyar, 2017; Anvari & Turkay, 2017; Arampantzi & Minis, 2017; Awad-Nunez et al., 2015; Cambero & Sowlati, 2016; Chávez et al., 2018; Govindan, Jha, et al., 2016; Jafari et al., 2017; X Jiang et al., 2018; Kesharwani et al., 2018; Miret et al., 2016; Mota et al., 2015; Rabbani et al., 2018; Roni et al., 2017; Varsei & Polyakovskiy, 2017; L. Zhu & Hu, 2017)
	Stochastic	***Eco + Env***
		(Asadi et al., 2018; Azadeh et al., 2017; Brandenburg, 2015; Ebrahimi, 2018; Fahimnia & Jabbarzadeh, 2016; Fazli-Khalaf et al., 2017; Gargalo et al., 2017; Govindan et al., 2015; Khorasani & Almasifard, 2018; Rahmani Ahranjani et al., 2017; Rajkumar & Satheesh Kumar, 2015; Tosarkani & Amin, 2018; Yılmaz Balaman et al., 2018; Zeballos et al., 2018)
		Eco + Soc
		(Afshari et al., 2016)
		Eco + Env + Soc
		(Fattahi & Govindan, 2018; Feitó-Cespón et al., 2017; Ghaderi et al., 2018; Jabbarzadeh et al., 2018; Mota, Gomes, et al., 2018; Mousavi Ahranjani et al., 2018; Osmani & Zhang, 2017; Zahiri et al., 2017; Zhalechian et al., 2016; Y. Zhang et al., 2016)

Eco (Economic criteria), Env (Environmental criteria), Soc (Social criteria)

5. Applications

The current section presents an analysis regarding the origin and the industrial context of the studies in the review. The goal of the section is to classify and discuss the published works from 2015 to 2018 according to their application area or economic sector and the continent where the case study took place. The classification per country has been intentionally divided into OECD and non-OECD countries, since OECD countries promote the adoption of sustainable energy policies, economic growth, prosperity, and sustainable development. The classification aims to identify a relation between these national policies and the study on sustainability at supply chain level.

According to the U.S. Mission to the OECD, the 37 countries belonging to the organization account for near to 63% of the world gross domestic product (GDP), more than 75% of global trade, are home of about 20% of the population of the world and represent more than half of global energy consumption (U.S Mission, n.a). In 1990, emissions of CO_2 from OECD countries represented more than 50% of global emissions, but because of the increasing global concern about environmental protection, these economies have made efforts to control and reduce the number of emissions from their industrial activities and nowadays their emissions represent about 38% percent of global emissions of CO_2. However, as mentioned by (Wiedmann & Lenzen, 2018), this number, rather than a better environmental performance, might represent a burden shift from developed countries to developing ones. This situation is partially evidenced by the high number of cases addressing sustainable supply chains in developing economies in non-OECD countries as shown in Figure 2.7. *Number of studies per continent*
.

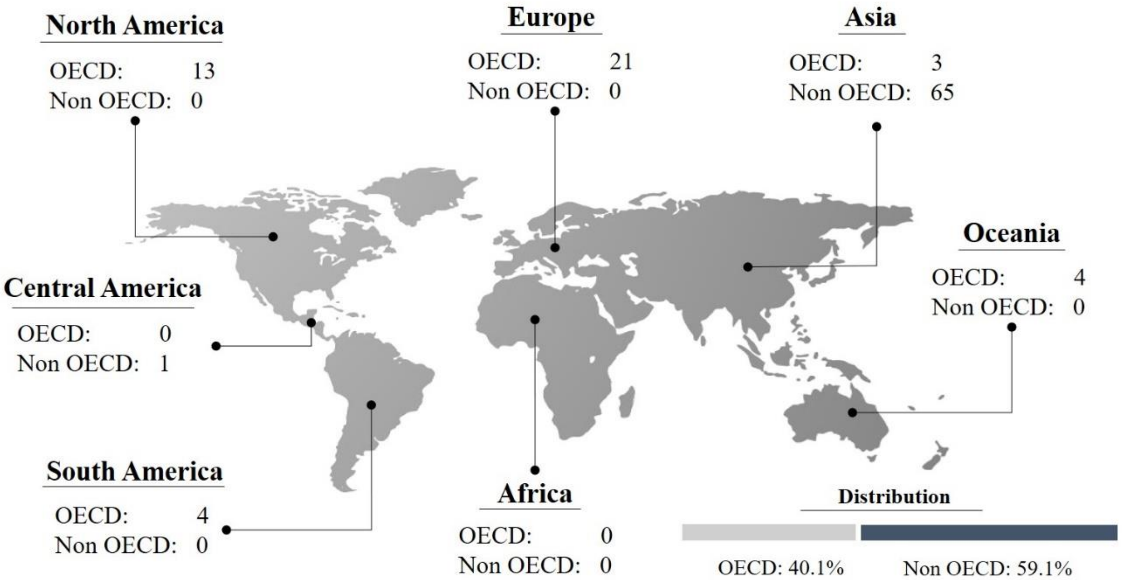


Figure 2.7. Number of studies per continent
(Moreno-Camacho et al., 2019)

Globalization has brought significant changes in supply chains networks, leading to geographical separation of production and consumption zones (Wiedmann & Lenzen, 2018). Over the last decades, an increasing offshoring strategy has taken place among manufacturing companies; low labor costs are often the primary reason for companies to relocate their operations, considerations like lesser environmental taxes and the advantages of economies of scale in high volume production result being sensible factors for companies to move their operations abroad. The industrialization process of these regions results in a change of the scale of environmental and social impacts.

In the 1990's, China was the preferred destination to relocate operations from companies, the movement to other countries in South Asia, Africa, and Latin America took place after (Xuemei Jiang & Green, 2017). Figure 2.7. *Number of studies per continent*
shows that about 60% of the total studies addressing sustainability in the SCND problem are cases from Asia, being Iran, China, and India the countries with the highest contributions. The rising concern about sustainable development in China and India is influenced by the accelerated growth in both production and consumption emissions because of the industrialization process. In 2017 while on the one hand some of the OECD members countries experienced decreases in their total amount of energy-related CO_2 emissions, including the United States, the United Kingdom, Japan, and Mexico, on the other hand, Asian economies accounted for two-thirds of the global increase in carbon emissions, with China and India being the countries with the most significant growth (IEA, 2017).

As pointed out by (Babazadeh, Razmi, Pishvaee, et al., 2017) the high number of applied cases in Iran is due to the national concern for fuel production and its consequences for environment and society. Iran has an abundant source of fossil fuels and is one of the biggest exporters of crude oil around the world. However, due to the emissions caused by extraction and processing, some cities deal with serious issues having negative impacts on environmental and socially unsustainable development. Air quality causes affectations such as skin and respiratory diseases, acid rain, and unacceptable living conditions in these cities. For this reason, state entities have increased budgets for the promotion of alternatives biofuels, which has yielded to new research in biomass supply chain design, which apparently has contributed with the mentioned results.

Surprisingly, from the review, no study cases addressing sustainable supply chain design were found in African countries. Makan & Heyns (2018) address the implementation of sustainable transport management practices for South African road freight transport. The work identifies that the main drivers to the adoption of sustainable activities include pressure from consumers and brand protection, pressure from top management and cost saving and revenue. Additionally, they point out some of the main barriers to its adoption that involve lack of government support, lack of understanding of the cost and insufficient manpower. Similar conclusions are yielded by Agyemang et al. (2018) who also mention initial implementation cost of green practices, difficulties to assess environmental sustainability performance, and lack of integrated management information and traceability systems as a barrier to the redesign of green supply chains mainly in West African countries.

Regarding the sector of application, manufacturing of electronic components and production of energy from biomass are the most represented sectors applying sustainability criteria in the SCND and partner selection decision. Notably, most of the cases studied focus on the bioenergy sector, which links the agricultural and the industrial sectors seeking for partially replacing of fossil fuels for more sustainable energy sources. However, most of the studies focus on generic environmental impacts coming from the distribution process and facilities location, but factors in both, environmental and social dimensions in the agricultural sector are scarcely involved into the decision-making process. Indeed, Grant, D. B., Trautrims, A. and Wong (2017), stated that, in the literature, there are numerous studies developed in manufacturing industry cases, while the agricultural sector has received less attention, despite the known social characteristics of its participants in the first tier (i.e., farmers) and the representative contribution that it sectors made to the total GHG emissions at global level.

As far as the electronic component market is concerned, the treatment or disposal of electronic components at the end of life is one of the most significant threats affecting its sustainable development. The European directive on waste electrical and electronic equipment (WEEE Directive) and the Restriction of Use of Certain Hazardous Substances (RoHS Directive) have been promoting the creation of schemes that involve safe and responsible collection, recovery and recycling procedures for all types of electronic waste. Studies addressing sustainability in this sector often used an approach of closed loop supply chain. The total environmental impact from raw materials, assembly, and production process, recovery and disposal are evaluated, usually, through quantification of CO2 equivalent emissions, or directly by the calculation of produced waste (Anvari & Turkay, 2017).

The automotive and fashion sectors have gained increasing interest respect to the results in (Eskandarpour et al., 2015). The textile industry is a high water consumption sector (Jafari et al., 2017) and energy intensive (Fahimnia & Jabbarzadeh, 2016), hence, those criteria are usually evaluated in this context. Finally, sector such as construction, information, and communication technology, and e-commerce present a low frequency of applied cases, although the sectors are getting increasing attention from media and civil society. Table 2.2 presents a summary of the classification of studies by sector.

Table 2.2. Number of studies by economic sector from 2015 to 2018
(Moreno-Camacho et al., 2019)

Sector	*Total*	*Sector*	*Total*
Bioenergy	25	Commerce	4
Technology	19	Agrobusiness	3
Food & Beverage	12	Pharmaceutical	2
Industrial goods	10	Timber	2
Automotive	9	Mining	2
Fashion	7	Construction	1
Energy	6	Information & Communication	1
Chemicals	5	Steel	1
Home & Office products	4		

As displayed in Table 2.2 agricultural supply chains have been received little attention, despite of the notorious convergence of sustainability issues in the sector. For instance, it is well known that the advancement of agri-food industry deals with insurance viability and competitiveness while promoting good environmental practices and improve livelihood and economic conditions in rural areas. The next section is devoted to explaining the characteristics of agri-food supply chains and its relationship with sustainable development as part of the description of the study subject of this work.

6. Sustainability in Agri-food supply chains

Broadly speaking, agricultural industry comprises a width set of procedures and its related services, wherein natural resources are used to produce commodities such as food, fiber, fuels, and forest products, among others. Specifically, agri-food supply chains comprise a series of activities from production to distribution to bring farm products from farm to market (Tsolakis et al., 2014). According the characteristics of the product these can be classified in supply chains for fresh agricultural products or supply chains for processed food products (Naik & Suresh, 2018). According to Tsolakis et al. (2014), agri-food supply chains are differentiated from other types of chains, due to the short life-cycle of goods, the seasonality in harvesting and production operations, the high product differentiation, the specific requirements in transportation, storage conditions and material recycling, the need to comply local and international legislation and regulations regarding food safety and public health, as well as environmental conditions.

In many countries, especially in developing countries, agri-food sector plays an essential role in the economy by being a significant contributor to GDP (Gebresenbet & Boso, 2012) and it constitutes an essential agent in the economic, social and environmentally sustainable development of rural communities (Naik & Suresh, 2018). According to the World Bank, this sector accounted for almost one-third of the global GDP in 2014. Moreover, due to population growth, advances in transport, information and communication technology, the agricultural sector has an annual growth rate of over 6% during the last decade, and its production will be twofold by 2050 (FAO, 2018). The sector is especially important in Latin America and the Caribbean region where it represents the 14.1% of total generated employees in the region in 2018 (OECD/FAO, 2019), meanwhile in the European Union it accounted about 4.4% of total employment by 2017 (Eurostat, 2019).

Despite the economic growth of agri-food sector in the last years, rural areas, where it takes place, still tending to lag as regards in social and economic conditions. For instance, according to the European Comission (2007), incomes in rural areas is near 20% lower than in urban areas, and rural areas present higher unemployment rates. Agri-food sector also plays a significant role in the environment. Agriculture, forestry, and land-use change that account for 25% of greenhouse gas emissions. Sustainability in the food industry is an issue receiving increasing attention in the last years since growing population generates an enormous pressure in food supply (Rohmer et al., 2019). The current consumption behavior affects agro-ecological resources, food security, and health, representing a critical issue for both consumers and producers (Naik & Suresh, 2018).

There are unique characteristics of agri-food supply chains affecting sustainability such as soil use change, water consumption, effects on the phosphorus and nitrogen cycles, waste disposal, social development, among others, that become relevant factors within the configuration of the network. For example, in order to reduce the wastes generated along the agri-food supply chain, as an indirect approach to address the environmental impact, (Caicedo Solano, García Llinás, & Montoya-Torres, 2020) proposed an innovative framework to couple Lean Thinking principles with Operations Research techniques. This framework was later validated by (Caicedo Solano, García Llinás, Montoya-Torres, et al., 2020). Moreover, one of the significant social issues affecting sustainability in the sector, is the practical exclusion of primary suppliers in the chain. Due to the scarcity of resources and limited access to information, smallholders might be unable to adopt sustainable practices. The situation is even worst in developing countries where the lack of access to technology threatens the productivity and competitivity of small farmers.

The issue has been recently addressed by some authors. For instance Accorsi et al. (2016) developed a linear programming model to the design of a zero-emission supply chain with an application in the potato farming context. The model considers a land-use assessment for the location of crops, processing facilities, warehouses, forests, and renewable energy production fields. Overall emissions associated with crops and logistics activities are compensated by the planting of forests and the use of renewable energies. Escobar et al. (2017) propose an optimization model for the design of the supply network of the fish industry. The authors present a single objective model including a penalty cost over the production of fat waters, and organic solid waste at fish farms. Miranda-Ackerman, Azzaro-Pantel, and Aguilar-Lasserre (2017) present a non-linear multi-objective model for the green supply chain network design of orange juice. The environmental objective calculates the CO_2 equivalent emissions generated by the orchard production, pasteurization process, bottling, and transportation activities. The model considers four agricultural practices according to the intensity of the use of agrochemicals, as well as a set of different processing and bottling technologies, which differ in the associated environmental impacts. The authors present a genetic algorithm and a multicriteria decision-making tool to solve the model. Fang et al. (2018), address the design of a cold supply chain network for transportation of fresh products to China from ports to retailers. The environmental objective aims to minimize the amount of CO2e emissions from distribution centers operations and freight transportations activities, while to the economic pillar considers minimization of total costs.

7. Conclusions

This chapter presented a review of the academic literature addressing sustainability and its link with supply chain network design. The review presented a particular focus on metrics and modelling approaches. Moreover, a classification regarding sectors and countries of application is done. The review highlighted how researchers in the supply chain management field have paid more attention to economic and environmental criteria, than to social criteria. However, there is an increasing interest on dealing with the three dimensions of sustainability with fairness, therefore, in the incremental inclusion of criteria, social dimension has becoming a relevant topic. The design of the whole supply chain network is a critical decision in supply chain management. For example, decisions regarding the number, location, and capacity of facilities, the selection of suppliers and transportation modes, the allocation of demand, etc. have a strategic impact on economic, as well as in environmental and social performance.

In this regard, the economic dimension is still mainly represented by criteria in the financial performance field. Although some authors highlight the dynamical approach of sustainability and the need of inversion in the long-term to reach steady state in sustainable development, the Net present value (NPV) objective have been used in a lesser extent (Barbosa-Póvoa et al., 2018; Kannegiesser et al., 2015). Opportunities exist to propose solution methodologies evaluating sustainability in the long term and its impacts on monetary flow, as investment is required to reach sustainable development.

Regarding the environmental dimension, air pollution remains the most common criterion at assessing environmental impacts. Since the energy sector and the transport sector are greatest contributors to GHG emissions in developing economies, most of the studies addressing supply chain network design focus on the partial evaluation of direct emissions coming from operation facilities and transportation activities, even in studies involving agricultural activities. This consideration might be reevaluated at assessing agricultural supply chains in which the greater contribution to environmental impacts is caused by production activities at farms.

Regarding the sector of application, several advances have been made in bioenergy and electronic component sectors, to assess environmental and social performance at the strategic level of supply chain planning, mostly because of regulatory framework in these sectors. There are multiple opportunities to research on agricultural applications, they start to gain an essential place in the literature, considering the period of study from 2015 to 2018. Since, different crops required different growing times, different level of water, different harvesting techniques, and different consideration of distribution also, as in the case of the cold chain. Besides, there are valuable opportunities for further research in the agricultural and food, automotive, industrial and textile sectors due to their own characteristics of high-water consumption and labor-intensive activities. It is even more crucial because with the globalization, environmental and social footprint spread out affecting, mainly, population of developing countries.

Finally, we can mention that lack of comprehensive supply chain design criteria might drives into partial solution with low impacts on supply chain sustainability. Therefore, a holistic perspective of supply chain is required to assess sustainability at supply chain level. In this regard, it is required to work in at least three paths. First, the definition of suitable indicators for the three dimensions of sustainability, ensuring the availability of data to measure them. Second, the definition of sustainability objectives to compare performance from different configurations and desirable states in the future. Last but not least, the construction of suitable models to optimize the multi-dimensional performance of sustainable supply chains (Beske-Janssen et al., 2015). The following chapters will be devoted to present different approaches to deal with sustainability issues for supply chain design from a modeling perspective.

Chapter 3 Single objective model

Partial content of this chapter is published in Moreno-Camacho, C. A., Montoya-Torres, J. R., & Jaegler, A. (2020). Designing a Sustainable Supply Chain Network. In Service Oriented, Holonic and Multi-agent Manufacturing Systems for Industry of the Future. SOHOMA 2019. Studies in Computational Intelligence, vol. 853 (pp. 15–26). https://doi.org/10.1007/978-3-030-27477-1_2

This chapter presents a single-objective model to the design of a supply chain, considering economic, environmental and social objectives. Each objective is evaluated separately to measure the impact of sustainability criteria on the structure of the network. The model focus on a producer company.

1. Literature review

Although the definition of sustainable development and sustainability involves several aspects, evidenced by the multidisciplinarity of concepts included in the sustainable development goals (SDG's) (UN General Assembly & United Nations, 2015), sometimes, in the context of supply chain design decisions, at managerial level, this complexity is reduced to the evaluation of a single objective. As stated by Eskandarpour, Dejax, Miemczyk, & Péton (2015) this approach keeps the focus on logistics operations, while integrate new features into decision making process.

As far as modeling techniques are concerned, the use of multicriteria evaluation techniques is widespread to the selection of suppliers as well as to the definition of potential locations that meet a selected set of criteria that respond mostly to environmental requirements. For instance, Galvez, Rakotondranaivo, Morel, Camargo, & Fick (2015) address the location of a biogas plant to valorize organic residual waste. The authors propose a hybrid method combining MILP and Analytical Hierarchical process. At first a location problem is solved considering three different scenarios, and then the optimal solution of these scenarios is compared considering different criteria including total CO_2 emissions by waste transportation activities. Izadikhah & Saen (2016) present a new ranking method combining Data Envelopment Analysis (DEA) and discriminant analysis to solve location planning problem. Productive, supportive, logistics and environmental factors are evaluated using geographic information, to define the best location to the construction of facility among a set of candidates locations. Neumüller, Kellner, Gupta, & Lasch (2015) present an Analysis Network Process for the selection of distribution, including economic, environmental, and social sustainability aspects. In the examples above, consideration of sustainability criteria occurs outside of optimization models. Sometimes multi attribute decision making methodology (MADM) feeds the model with a set of promising alternatives considering environmental and social key indicators and sometimes MADM are used after optimization to compare a set of solutions regarding sustainability aspects.

On the contrary, other approaches consider environmental and social key indicators within optimization model. When the case, environmental and social criteria are involved into the optimization problem, the former is usually measured through quantification of GHG emissions as a tacit agreement on its relationship with climate change. While to the social dimension, there is no complete agreement in what must be measured, however, most of the factors are related with working conditions, particularly, employment and health and safety (Moreno-Camacho et al., 2019). In this regard, two different approaches are utilized in the related literature. On the one hand the use of environmental and social constraints, establishing upper or lower bounds to the key indicators within each dimension as appropriate. For example, Xu et al., (2017) deal with the design of a multi-national reverse supply chain to collect waste, considering emissions through the chain regarding the flows of solid waste products. To solve the problem a MILP robust technique is employed considering a cap on the number of emissions. Multiple values for the cap are tested in separate computation experiments. Results show higher values on the emission cap are related with lower total costs and slight changes on network structure. Mainly, lower values on cap emissions promotes performance of inner local activities discouraging international transport of waste.

On the other hand, a second approach to consider sustainability criteria within optimization models is related to monetarization of ecological impacts. This assumption of interchangeability among economical and natural resources is, according to Feitó-Cespón, Sarache, Piedra-Jimenez, & Cespón-Castro (2017), a branch of neoclassical environmental economics, which grounds that natural resources can be utilized and replaced with no limits as long as it provides human society with a wide array of functions and services. The idea of weak sustainability has been discussed widely within the scientific community, debating the relationship between well-being and nature, and the compensability through monetary values. For more on this regard the interested reader might find useful the work of (Ang & Van Passel, 2012; Biely et al., 2018; Randal Davies, 2013). Here the review is limited to the description of the approach in the sustainable supply chain field rather than state a position on the issue.

For instance, Clavijo Buritica, Escobar, & Triana Sánchez (2017), address the problem of designing a supply chain to the fish industry. The authors consider an economic objective which include monetary penalties for the yield of surplus waste at fish farms and fish production centers, since waste discharge might pollute natural water sources. Other authors work on supply chain design under carbon emission policies, which involve penalties on GHG emissions. Duarte, Sarache, & Costa (2016) propose a single objective model to the design of a biodiesel supply chain considering a cost over the undesirable ecological effects caused by CO_2 eq. emissions at biomass growth and pre-treatment activities, biofuel processing and material transportation through different levels. Three scenarios are evaluated considering different CO_2 emission cost. As expected, higher CO_2 prices are related with lower economic benefits. Moreover, with the data associated to the case study evaluated, variation in CO_2 prices does not end up modifying supply chain network structure. For instance, Zhou, Gong, Huang, & Peters (2017) consider a global supply chain in which carbon tariffs are imposed over products coming from countries with no carbon regulations to regulated countries. According to the results, higher carbon tariffs instead of motivating appropriation of cleaner technologies in non-regulated countries end up discouraging exports to countries where carbon tariffs are imposed. Interestingly, non-regulated countries are encouraged to adopt cleaner technologies when local production in regulated countries is not enough to meet the internal demand. Almansoori & Betancourt-Torcat (2016) address the problem of designing a network to the supply of hydrogen under emission constraints. The authors evaluate carbon cap as well as carbon tax policies separately, while consider CO_2 emissions coming from hydrogen plants and hydrogen distribution activities. The authors claim that regarding the structure of the supply chain the effect of carbon tax is equivalent to the implementation of a carbon target, although allocation of demand may have slight variations.

That said, the aim of the effort on this first chapter is to analyze how does environmental and social criteria affect the structure of the supply chain. Putting it differently, which is the impact of considering environmental and social key indicators in the location of facilities within classical optimization techniques for SCND. Therefore, the current chapter present a driven dimension analysis to the definition of a supply chain network, key indicators are selected in the three categories of sustainability and then three single objectives problems are solved to compare the yielded results.

2. Problem statement

This chapter addresses with the design of a supply chain when the decision concerning selection of suppliers, allocation of manufacturing and distribution facilities and transportation mode selection are guided considering different criteria from economic, environmental, and social dimensions, separately. The supply chain is composed of suppliers, manufacturers, warehouses, and retailers.

Formally speaking, we consider a forward supply chain, where a set of suppliers S with endless capacity, deliver raw material to a set of production facilities or manufacturers M with fixed and known capacity, who are the producers. Manufactured goods are delivered to a set of capacitated warehouses D who meets a set of demand points or retailers R. Additionally, we consider the possibility to choose among a set of automation technologies T in each one of the actives production facilities. Finally, to transport final goods from warehouse to retailers. We consider the possibility of use both, a conventional fuel vehicles fleet and electrical vehicles fleet. We consider each unit moving from a node to another one, incurring thus in a unitary transportation cost and generate an amount of CO_2 emissions during this trajectory. Each active manufacturer might operate equipped with a chosen technology, which is related with the number of jobs offered at the facility. Moreover, technology level decision has an impact on the environmental dimension due to by-products and related CO_2 emissions from production process. It is assumed that high automation levels are related with lower levels of greenhouse gas emissions due use energy efficiency, operational efficiency enhancement, and reduction of processing waste. However, it is also related to lower hand-work demand what causes low job offers and low impact in social development.

Regarding the warehouses, we consider handling product within warehouses as a source of CO_2 emissions, mainly derived from energy consumption during its transit through facilities. Besides, it is considered selection of a supplier causes a positive social impact due to the economical activation in the region. To this purpose each supplier is associated with a social sustainability factor φ_s representing social features and its impacts in equity, population, health among others as is proposed in Hutchins & Sutherland (2008). In this sense, supplier in less developed regions get higher φ_s since labor offering and economic involvement of this region are expected to represent higher benefits. Finally, there is a decision regarding the type fleet to use in the distribution of products from warehouses to retailers. The use of an electrical fleet has a reduction on the emissions caused by transporting but implies a greater cost than the use of conventional fuel vehicles.

The evaluated features have impacts into each one of the three dimensions of sustainability deemed. Hence, the definition of a network structure lead by each one of the evaluated dimensions might derive in several differences, since there are expected trade-offs between the key indicators. For instance, economic performance is negatively impacted by the number of suppliers and the use of electric vehicle fleet to final distribution. However, these conditions improve social and environmental performance, respectively. On the other hand, environmental performance is negatively impacted when a high number of suppliers is considered, due to spread transportation activities. The number of production facilities and technology decisions have opposite effects, regarding social and environmental dimension, and clearly these decision affect economic performance. Lastly, although the number of warehouses in operation and the use of electric fleet has non evaluated contribution to social performance it affects environmental and economic performance.

3. Mathematical model

The current section presents the proposed Mixed-Integer Linear Programming (MILP) model to deal with the problem described above. Definition of sets, variables, parameters, constraints, and the different objective functions to be evaluated on the mathematical are as follows:

Sets

s suppliers	with $s = 1, 2, \dots, S$
m manufacturers	with $m = 1, 2, \dots, M$
d warehouses	with $d = 1, 2, \dots, D$
r retailers	with $r = 1, 2, \dots, R$
t technologies	with $t = 1, 2, \dots, T$
f fleet	with $f = 1, 2, \dots, F$

Parameters

dem_r: demand of retailer r

ca_{mt}: production capacity of manufacturer m equipped with technology t

mof_m: minimum expected operational efficiency of manufacturer m

ca_d: inventory capacity in warehouse d

$msup_s$: minimum order quantity from active suppliers

Cost parameters

cp_{mt}: unitary production cost at manufacturer m equipped with technology t

ct_{sm}: unitary transportation cost from supplier s to manufacturer m

ct_{md}: unitary transportations cost from supplier m to warehouse d

cfx_{mt}: fix operational cost of manufacturer m equipped with technology t

cfx_d: fix operational cost of warehouse d

CO_2 emissions parameters

e_{sm}: contribution of CO_2 emissions per unit during transportation from supplier s to manufacturer m

e_{md}: contribution of CO_2 emissions per unit during transportation from manufacturer m to warehouse w

e_{dr}: contribution of CO_2 emissions per unit during transportation from warehouse d to retailer r

ep_{mt}: contribution of CO_2 emissions per unit during production process at manufacturer m equipped with technology t

ep_d: contribution of CO_2 emissions per unit during handling product at distribution center d

Social parameters

j_{mt}: number of jobs created in the facility of manufacturer m equipped with technology t

φ_s: social index associated with active supplier s

Auxiliar parameters

G: Big number

Variables

Integer decision variables

x_{sm}: units of raw material transported from supplier s to manufacturer m

y_{mtd}: units of final product transported from manufacturer m equipped with technology t to warehouse d

w_{dfr}: units of final product transported from warehouse d to retailer r using fleet type f

Binary decision variables

δ_{mt}: 1 if manufacturer m equipped with technology t is open, 0 otherwise

γ_d: 1 if warehouse d is open, 0 otherwise

λ_s: 1 if supplier s is active, 0 otherwise

Constraints

Then, the classical equations to ensure meet demand, capacity limitation and flow equilibrium in the supply chain network are presented.

Capacity facility constraint

$$\sum_m x_{sm} \leq G * \lambda_s \qquad \forall\, s \qquad (1)$$

$$\sum_m x_{sm} \geq msup_s * \lambda_s \qquad \forall\, s \qquad (2)$$

$$\sum_s x_{sm} \geq \sum_t \delta_{mt} \qquad \forall\, m \qquad (3)$$

$$\sum_d y_{mtd} \leq ca_{mt} * \delta_{mt} \qquad \forall\, m, t \qquad (4)$$

$$\sum_d y_{mtd} \geq mof_m * ca_{mt} * \delta_{mt} \qquad \forall\, m, t \qquad (5)$$

$$\sum_{r,f} w_{dfr} \leq ca_d * \gamma_d \qquad \forall\, d \qquad (6)$$

Demand and equilibrium flow constraints

$$\sum_{d,f} w_{dfr} = dem_r \qquad \forall\, r \qquad (7)$$

$$\sum_{s} x_{sm} = \sum_{d,t} y_{mtd} \qquad \forall\, m \tag{8}$$

$$\sum_{m,t} y_{mtd} = \sum_{r,f} w_{dfr} \qquad \forall\, d \tag{9}$$

Technology selection constraint

$$\sum_{t} \delta_{mt} \leq 1 \qquad \forall\, m \tag{10}$$

Non-negative integer variables constraints and binary constraints

$$x_{sm}, y_{mtd}, w_{dfr} \in \mathbb{Z}^{+} \qquad \forall\, s, m, d, t, r \tag{11}$$

$$\delta_{mt}, \gamma_{d}, \lambda_{s} \in \{0,1\} \qquad \forall\, s, m, d, t \tag{12}$$

In the formulation above, constraints (1) and (2) ensure that only an active supplier can send units of material raw. An active supplier refers a supplier that has been selected to be part of the supply chain providing manufacturers with raw material. Equations (3) ensures units coming from suppliers are delivered only to manufacturers in operation, avoiding extra open facilities in the case where the total number of jobs is maximized. Equations (4) and (5) define upper and lower boundaries for production quantity at manufacturing facilities, respectively. Both equations, (4) and (5) are necessary to avoid excess of open production facilities in the case where the total number of job opportunities is maximized. In fact, to avoid unrealistic results when social performance guides the configuration of the network, a minimum operational efficiency index is fixed in equation (5). It ensures that an open manufacturer facility must produce at least a fixed quantity of units to validate hiring workers. That might be understood as a minimum productive performance at manufacturers. Equation (6) allows warehouses to cater retailers according to its capacity. Constraint (7) warrants demand for each retailer is satisfied. Equations (8) and (9) ensure the material flow balance between suppliers and manufacturers and between manufacturers and warehouses, respectively. Constraint (10) at most one automation level can be assigned to each manufacturing plant. Lastly, the description of decision variables is given at constraints (11) and (12).

Objective functions

To assess the dimensions of sustainability (i.e., economic, environmental, and social) three different objectives were proposed. The first objective (Z_1) is to minimize the total cost of supply chain operation as a measure of the economic performance. Equation (13) shows how this cost is calculated, including the fixed cost to operate several production facilities and warehouses as well as the variables cost for the total amount of raw material transported between the suppliers and the manufacturers and the goods produced and transported towards retailers.

$$Z_1 = \sum_{m,t} fx_m * \delta_{mt} + \sum_{d} fx_d * \gamma_d + \sum_{s,m} ct_{sm} * x_{sm} + \sum_{s,m} (ct_{md} + cp_{mt}) * y_{mtd} + \sum_{s,m} ct_{dr} * w_{dfr} \tag{13}$$

Total number of CO_2 emissions during material forward flow throughout the supply chain was selected as indicator to define the network structure from an environmental perspective. The sum of the total amount of metric tons of CO_2 derivate from the raw material and final products transportation, the CO_2 emissions caused by production process in production facility with a specific technology and the emission from a warehouse open is shown in the Equation (14). Worth to point out, features of reverse logistics or closed-loop supply chain are not addressed in this objective.

$$Z_2 = \sum_{s,m} e_{sm} * x_{sm} + \sum_{m,t,d} (e_{md} + ep_{mt}) * y_{mtd} + \sum_{d,f,r} e_{dr} * w_{dfr} \tag{14}$$

For the social perspective assessment two factors have been selected and expressed in a composite indicator, particularly total amount of job opportunities created by manufacturer m using technology t and social impact caused by supplier's selection s. In this case, the proposed metrics have different dimensions, with the objective to join them together in an only one expression, a scalarization method was applied (Ehrgott & Wiecek, 2005). For each one of the metrics in the social dimension the range of its function is calculated (i.e., the maximum and the minimum possible values when each metric is evaluated separately). Let i the index for the metrics, let Max_i and Min_i the maximum and the minimum value of the metric i, respectively, calculated separately. It should be noted that in this case the optimal value for the metric i (i.e., Opt_i) corresponds to Max_i value for both factors, since the objective is to generate the higher social impact through hiring the highest number of employees and promoting business with suppliers in less developed regions causing the highest possible impact.

For each one of the two proposed measures regarding the social performance a value b_i is calculated, as is shown in equation (15). b_i represents the deviation of the measure value i (i.e.,v_i), from its optimal value.

$$b_i = \frac{|Opt_i - v_i|}{Max_i - Min_i}; \qquad with \;\; 0 \leq b_i \leq 1 \tag{15}$$

Then, the objective consists of to minimize the bias of the metrics values respect to its optimal value in the expression (16).

$$Min\, Z_3 = \sum_{i} b_i \tag{16}$$

The model aims to find the best possible configuration of supply chain network that optimizes each one of the proposed economic, environmental, and social performance measures, separately. To identify differences in the structure network when the decision is clearly biased by one of the dimensions of sustainability. Nevertheless, in any case, the model ensures to meet minimum productivity requirements, in a competitive context to avoid unrealistic outcomes.

4. Results

To test the performance of the proposed model a dataset is constructed considering probability distributions to the scenario presented in (Montoya-Torres, 2015) for the design of a supply chain in a high-variety production environment. The model considers the existence of 30 potential suppliers, 20 manufacturing facilities, 30 warehouses and 15 retailers. This section presents the results of the numerical example. All experimental tests were conducted on a personal computer with an Intel Core i5 4200U processor, 1.60 GHz with 8.00 GB of RAM. The proposed model was programed using GAMS and solved using the mixed-integer programming solver ILOG CPLEX 12.2. Not analysis is considered over computational times, there are not relevant differences interesting to point them out.

During the analysis, the best possible supply chain structure was found evaluating the economic, environmental, and social performance, separately. As it was explained before, the two proposed metrics to evaluate social impact into the supply chain have not the same measure units, consequently a normalization procedure was carried out for those metrics as presented above. The minimum and the maximum possible value (i.e., range of function for each metric) is shown in Table 3.1. So, the minimum number of created opportunities jobs is 272 jobs and maximum 461 jobs, the scenario in which the manual process is favored at every in-operation manufacturer. Finally, the indicator to social sustainability supplier assessment has a minimum value of 0.307 and a maximum value of 4.656 in the case the great number of suppliers are chosen to increase the social impact to the supply chain.

Table 3.1. Range of social performance metrics

Metric	Min_i	Max_i
J_{mt}	272	461
φ_s	0.307	4.656

Table 3.2 presents the results of every key indicator when the decision is guided by the objective in the second row. Optimal values for each dimension one of the measures in the three dimensions of sustainability are in bold. The different structures of the supply chain network based on the decision criteria of each one of the dimensions of sustainability are presented in Figure 3.1

Table 3.2. Results for the separated evaluations

	Objective		
Dimension	Economic	Environmental	Social
Economic	**8.80931E+07**	1.16083E+08	1.79956E+08
Environmental	62.4810	**30.6245**	90.8294
Social	1.6334	1.8515	**0.1380**
Jobs	272	223	448
Suppliers	1.901	2.080	4.3550

As shown in Figure 3.1 when the decision is based solely on the economic criteria the network is composed by four suppliers (black circles in external circumference), four manufacturing facilities (black squares), all of them with the highest automation level and ten distribution centers (DC's) (black triangles in the internal square),to meet the demand of the fifteen retailers. Besides, the total demand is dispatched using conventional fuel fleet. A total number of 272 jobs offers are generated and 4 suppliers participate into the chain. Since less developed areas are usually located far away from market regions, representing higher transportation costs, suppliers in remote areas are barely considered to be part of the supply chain structure.

In the case, when the decision is guided by the environmental criteria four suppliers are chosen, four manufacturing facilities are opened, same number as in the previous case, with the highest automation level. Four DC's are selected to deal with the demand. Unlike the previous case, all goods are delivered using the electric fleet. The total cost increase about 33% meanwhile the emissions of CO_2 reduced near to 51%, showing the existent trade-offs between these competing objectives. As mentioned before suppliers in remote areas are neglected to be part of the supply chain, since transportation of raw material from those to manufacturer plants imply a considerable increase on carbon emissions. This condition results particularly important in developing countries where rural road infrastructure usually is in poor conditions. This particular feature and its impacts on sustainability development, particularly in environmental performance have been addressed in Chen, Hu, Gan, & Qiu (2017).

Finally, the last case when social criteria determine the structure of the network, the number of suppliers increases up to seven. Job offers are promoted by a higher number of manufacturing facilities, six in this case, all of them equipped with the lowest automation level, leading to a manpower intensive production system. In this case the number of DC's opened is fourteen and the distribution of products use both, conventional and electric fleet in a relation 3 to 1, approximately. The total cost is almost the double respect to the first scenario and the environmental impact caused by the supply chain is also the worst. The total amount of emissions is almost three times compared with the best scenario. The hiring rate in the social decision-based scenario is about 65% greater than the same metric in the first scenario.

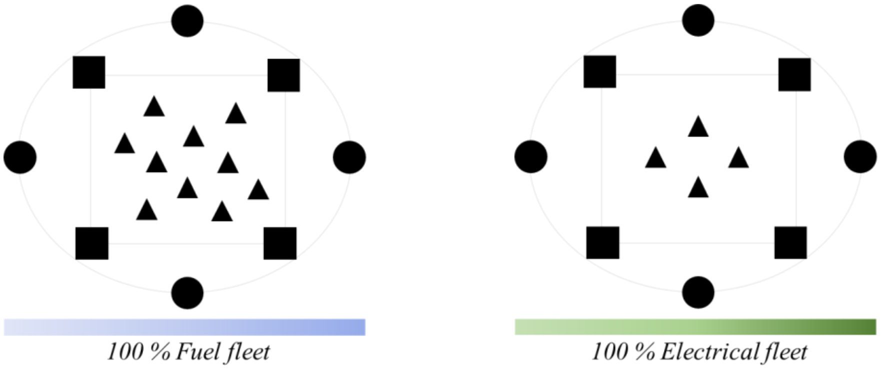
Is worthy to note that the previous results show the best performance of the supply chain of each one of the dimensions of sustainability. However, the definition of what must be a sustainable supply chain is not necessarily related to one of these extreme points. Clearly, is not possible to obtain the best of the three scenarios at the same time. However, the dynamic condition of sustainable development must lead to the companies in the supply chain to establish acceptable interval of operations for each one of the evaluated criteria. Supply chain design as key element on the strategic decision level of supply chain management must deal with dynamic decisions impacting the evolution of the chain in the oncoming time.

Furthermore, to change from one configuration to another great investments are required. For instance, to change from a conventional fuel fleet to an electrical fleet, required either, replacement of a full fleet of trucks or development of a third-party logistics who oversee the distribution. In fact, this decision is rarely assumed for one period to another. In this sense separate evaluation of sustainability criteria is useful to determine current limits of operation and as well to define limits to the acceptable intervals of operation.

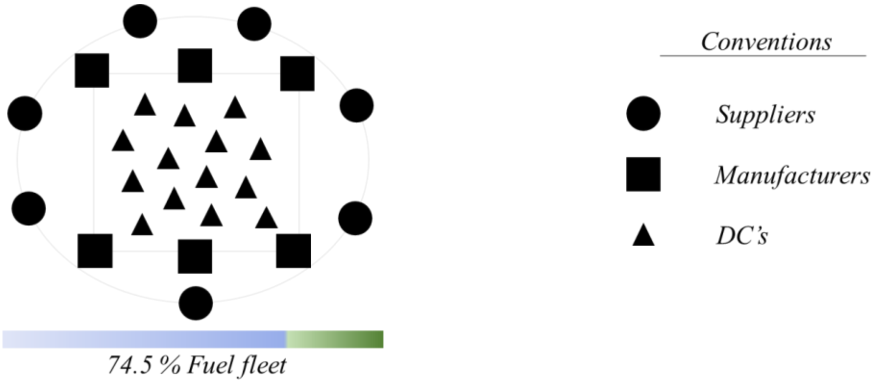
5. Conclusions

This chapter present the first effort during the research process to evaluate the differences in the supply chain network structure, when the decision is guided by each one of the dimensions of sustainability, separately. Results show how the structure changes in relation with the assessed criteria, pointing out the trade-off interactions between the objectives of sustainability in the supply chain field context.

Moreover, it presents a starting discussion about sustainable considerations at supply chain level. Further of establishing a result the separate performance assessment is useful to identify acceptable levels of operations in each one of the dimensions of sustainability, bringing into the focus the notion of dynamic in the sustainability concept. Since achieving optimum for one objective requires compromise of other objectives, it is required to establish acceptable values to every key indicator to consider a solution as sustainable. An additional interesting point related to supply chain structure is the required time to move towards a more sustainable structure. It is more evident when addressing sustainability assessment on existent supply chain networks or at facing disruptive technologies.



(a) Economic decision-based ***(b) Environmental decision-based***



(c) Social decision-based

Figure 3.1. Network structures

Therefore, on the one hand, there is room for developing models considering key indicators simultaneously, while consider targets for sustainable development in the context of supply chain design, to evaluate the impact of long-term decisions. In this sense, compromise between objectives is ruled by sustainability definition rather than decision-maker preferences. On the other hand, being time an important variable towards sustainable development, still interesting add dynamism within supply chain structure transformation.

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Chapter 4 Multi Objective Model

Partial content of this chapter is currently under submission for publication as: Moreno-Camacho C.A., Montoya-Torres, J.R., & Jaegler, A. (2021). Sustainable Supply Chain Network Design: A Study of the Colombian Dairy Sector, Annals of Operations Research

The current chapter presents a multi-objective optimization model to the design of a supply chain network. The chapter starts by presenting a brief literature review on multi objective optimization model to sustainable supply chain network, features and solution techniques. It highlights the role of decision maker preferences on sustainable supply chain design context. Unlike the model presented in the previous chapter, here, indicators of sustainability are evaluated at the same time to establish the location of production and warehouses facilities. The problem deals with the existence of conflictive objectives, therefore a Multi objective Optimization (MOO) technique is used to solve it. The analysis of the results opens the discussion regarding the need of defining objectives at assessing sustainability and presents an initial approach to it.

1. Multi-Objective Optimization

As mentioned in previous chapters SSCND bring economic, environmental, and social aspects into the spotlight, while considering strategical decisions for companies such as facilities location, technology production selection, supplier selection, demand allocation and transportation modes, among others. Although some environmental and social factors can be expressed in economic terms such as taxes over GHG emissions (Zakeri et al., 2015), or investment in community development programs. Other environmental, and especially some social factors, are not easily represented through a cost function, neither desired to be. As a result, the definition of a sustainable supply chain network from the operational research perspective becomes a Multi-Objective Optimization Problem (MOOP), and the modeling approach also becomes difficult, involving tradeoffs between conflicting objectives (Mota, Carvalho, et al., 2018). Indeed, as reported by (Eskandarpour et al., 2015; Moreno-Camacho et al., 2019) about three-quarters of the works addressing sustainable supply chain rely on multi-objective approaches. Nevertheless, having social dimension received less attention, many of the works focus on bi-objective models considering economic and environmental performance assessment.

Most of the works consider the existence of conflicting objectives in the pursuit of financial performance and environmental compliance. For instance, environmental impacts caused during both the construction and the operation phase of facilities, might include, discharges of solid wastes, water flows pollution, and noise and air pollution. Additionally, Anvari & Turkay (2017) recognized the antagonistic relation between environmental and social performances at the location of industrial facilities. Considering that the economic growth that boosts social development is regularly performed at the expense of natural resources. For instance, the construction of a new production plant in a specific region might represent job opportunities for its inhabitants, but also promotes the migration into the region, adding pressure on general community services such, hospitals, or schools, among others. As a matter of fact, the existence of conflicting objectives is a basic assumption for multi objective optimization. Otherwise, if all objectives improve and worsen under the same conditions, then the problem might be easily reduced to the consideration of a unique objective.

Formally, a multi objective optimization problem (MOP) is defined as:

$$\begin{aligned} &Minimize\ \{f_1(x), f_2(x), \dots, f_k(x)\} \\ &subject\ to \\ &\qquad x \in S \end{aligned}$$

Where $k \geq 2$ is the number of objectives and $x \in \mathbb{R}^n$ is a *n*-position vector containing the values for the decision variables to be determined in the problem. $S \subset \mathbb{R}^n$ is the set of feasible solutions implicitly determined by the set of constraints. Unlike single-objective optimization, where it is possible to determine between any given pair of solutions if one is better than the other, in multi-objective optimization there does not exist a straightforward method to determine if a solution is better than other. Different approaches to rank solutions are considered in the scientific literature (Bouyssou, n.d.; Li et al., 2017). In this regard, the Pareto dominance relation is the most commonly adopted method in multi-objective optimization to compare between a set of solutions (López Jaimes et al., 2011). By definition, let $x \in \mathbb{R}^n$ be a vector with i coordinates $i \in \{1, \dots, n\}$, measuring positive attributes of a company such as, profit, service level, environmental benefits, among others. We say that vector x Pareto-dominates a vector $y \in \mathbb{R}^n$; denoted by $x \prec_{pareto} y$, if an only if $x_i \geqq y_i$ for all coordinates i, with strict inequality for at least one coordinate. Conversely, if coordinates represent negative or "bad" attributes, for instance, cost, defective products, pollution, layoffs, etc., vector x Pareto-dominates a vector y if and only if $x_i \leqq y_i$ for all coordinates of *i*, with strict inequality for at least one coordinate. Moreover, a solution vector x is Pareto optimal if there does not exist, in a given set of alternatives, a vector y such that $y \prec_{pareto} x$ (Voorneveld, 2003).

By virtue of the below definition of optimality, multi-objective optimization techniques usually find several trade-off solutions. In a variable space these vectors are referred as Pareto optimal decision vectors, while in objective space, are called Pareto optimal front (POF) (López Jaimes et al., 2011). Nevertheless, in practice, only one solution must be selected for implementation. For instance, having different cities for the location of facilities, only one point will be selected to establish it. Formally, two solution vectors belonging to the POF are equivalent, one is as good as the other, and it requires the involvement of a decision-maker, who provides subjective preference information to choose the best solution in a particular instance of the problem (Kaliszewski et al., 2016). Therefore, multi-objective problems might be understood as the combination of both, finding a set of Pareto optimal solutions and decision-making.

Mathematical programming techniques are classified considering how and when preferences from decision-maker are included into the searching procedure. Generally speaking, four approaches are considered in the literature, namely, *non-preference*, *a priori*, *a posteriori*, and *interactive* methods. Broadly speaking, in *non-preference* techniques, it is considered the decision-maker to not have specific assumption non bias on the solution. Therefore, after receiving the solution the decision-maker can make the choice to accept or reject it. One of the most common methods belonging to this category is the method of global criterion. For this method, the MOP is transformed into a single objective defined as:

$$\begin{aligned} & Minimize \left(\sum_{i=1}^{k} |f_i(x) - z_i^*|^p \right)^{\frac{1}{p}} \\ & subject\ to \\ & \qquad x \in S \end{aligned}$$

Where $z_i^*$is the ideal solution for the objective i, and k represents the number of objectives. The reached solution strongly stands on the value of p. Although the method yields a unique solution, different Pareto optimal solution could be calculated changing the value of p.

A priori methods for the solution of multi-objective optimization model entails the definition of preferences of the decision maker prior to the searching process. The preferences can be asked as a weight or relative importance of the objectives or as desired values for each objective. To this category belong approaches such as goal programming and lexicographic method. An example of the former is presented in (Miret, Chazara, Montastruc, Negny, & Domenech (2016) to the design of a bioethanol green supply chain. The authors consider total operational costs, environmental costs, and total jobs as indicators for each sustainability dimension. The resultant MOP is solved using a weighted goal programming. It is emphasized the advantages of using this type of methodologies in problems such as SCND which contains a large number of binary variables, and the POF may contain a very few numbers of optimal solutions. According to (Miret et al., 2016) in this type of problem, goal programming approach guides the problem within a bounded interval, limits the computational time, by avoiding the generation of complex research tree with no promising solutions, and ineluctably returns a feasible solution. (Nayeri et al., 2020) consider the design of a closed-loop supply chain network to the production and distribution of water tanks under uncertainty conditions. The authors consider total cost for the economic dimension, $CO_{2,}$ and asbestos emission for environmental dimension, and for the social dimension a composite indicator including jobs opportunities and lost working days caused by injuries during the establishment of facilities. A Goal programming method is utilized to solve the model while the preferences of decision-maker are included as desirable values between the range given by worst and best possible value to each objective.

In (Isaloo & Paydar, 2020) the authors present a comparison between *non-preference* and *a priori* methods to the design of a supply chain network for a plastic company. Total operational costs and environmental impacts are employed to address two sustainability dimensions. The results show the advantages of the weighted goal programming at reaching best solution with slightly higher computational times. Although *a priori* methods are intended to provide a unique solution to the decision-maker, several *a priori* methods, like weighted goal programming could be utilized to construct a pareto optimal front by solving multiple problems varying the weights. This method is also used in (Vafaei et al., 2020) at designing the distribution network for an e-commerce, considering economic, environmental and social criteria.

Regarding *a posteriori* methods, the decision-maker is involved after the MOP is solved. In this case a set of equally optimal solutions (POF) is generated, and the decision maker may choose the one that suits the best his or her preferences. Different methods might be employed to obtain a representative set of Pareto optimal solutions such as weighted sum method, epsilon constraint method, evolutionary multi-objective algorithms, among others. Indeed, the weighted sum method and the ε-constraint method are among the most common methods used to address SSCND. Weighted sum entails selecting a set of non- negative scalars, and strictly positive for at least one objective weights w_i, to compose a unique objective function combining all the objectives in the problem, such that $\sum_{i=1}^{k} w_i = 1$, where k represent the number of objectives. The transformed objective function become a linear combination of the different objectives, and the set of Pareto optimal solutions can be generated by parametrically varying the weights w_i in the objective function.

For instance, Afshari, Sharafi, ElMekkawy, & Peng (2016) present a weighted sum method to the design of a closed-loop supply chain under uncertainty. The authors consider customer satisfaction and supply chain total cost as objectives to evaluate social and economic dimensions, respectively. Colicchia, Creazza, Dallari, & Melacini (2016) address the selection of transit points and the allocation of demand for a chocolate manufacturer, considering environmental impacts coming from transportation and warehousing activities. Wang, Li, & Wang (2018) consider a bi-objective nonlinear programming model to the design of a supply chain, where different raw material might be selected, according to its purchase price, production cost and carbon emissions. In their work, profit maximization and carbon emissions minimization are considered in a weighted sum method. One of the most mentioned shortcomings of this method is its inability to deal with non-convex regions, in which the method shortfall at enumerates all the non-dominated solutions in the POF (Collette & Siarry, 2004).

A second method frequently employed to provide a representative set of the Pareto front, and which overcome the difficulty of nonconvexity is the ε-constraint method and its variations. In the ε-constraint method only one objective is optimized using the remaining objectives functions as a constraint in the model (Mavrotas, 2009). Parametrical variation in the right side of the constrained objective functions leads to obtain the efficient solutions of the problem. In particular, Murillo-Alvarado et al. (2015) propose an ε-constraint method to design a biorefinery supply chain based on residues of the tequila industry in Mexico. The authors consider simultaneously economic and environmental objectives. Total profit is the chosen indicator in the financial performance category, while environmental impacts associated with transportation and production activities are measured in Eco-Indicator points using the Eco-Indicator 99 method.

Cambero, Sowlati, & Pavel (2016) address the design of a bioenergy fuel supply chain considering economic as well as environmental impacts. Net present value (NPV) is used to calculate economic performance and the environmental objective aims to maximize GHG emission savings with the introduction of a biorefinery supply chain. To put it differently to maximize the difference in the total amount of GHG emissions between a baseline scenario with no biorefinery and an alternative scenario where forest and wood residues are harnessed to the operation of a biorefinery for the production of biofuels and energy. In the model, forest mill, biorefinery operations, biomass and biofuel transportation, and energy generation are considered to calculate CO_2 equivalent emissions (CO_2eq.). They used an augmented ε-constraint method to solve the problem. Same method is employed in Cambero & Sowlati (2016), the authors present an extension of the biorefinery supply chain network design, mentioned above, to consider social aspects. Here, social benefit is associated with the creation of new different types of jobs, including managers, supervisors, operators, truck drivers, among others. It considers unemployment rate by region and type of job. Other examples of ε-constraint method to solve sustainable supply chain design in different sectors are as follows, wine industry (Varsei & Polyakovskiy, 2017), biofuels (Gargalo et al., 2017; Nodooshan et al., 2018; Osmani & Zhang, 2017; Rabbani et al., 2018), home appliances (Urata et al., 2017), and agricultural products (Fang et al., 2018).

Multi-objective evolutionary algorithms (MOEAs) are nature inspired algorithms using population-based approach to construct a representative set of the POF for a specific problem. There at least to main objectives for evolutionary algorithms, to obtain a set of solution as close as possible to the POF and to find a set diverse enough to represent the complete POF. (Asadi et al., 2018) propose a bi-objective model for the design of a biofuel supply chain. In the model, the minimization of costs and impacts via CO_2e emission are considered to the performance in the economic and the environmental dimension, respectively. The authors compared the performance of Multi-Objective Particle Swarm Optimization (MOPSO) and the Non-Sorting Genetic Algorithm (NSGA-II) to solve this problem. In fact, evolutionary algorithms have gained attention in the SSCND context. (Miranda-Ackerman et al., 2017) present a genetic algorithm to the design of an orange juice supply chain, considering GHG emissions.

Finally, in the fourth category *interactive* methods, here, the preferences of the decision-maker are iteratively considered through the searching process. A typical interactive method starts with an initial pareto optimal solution, the preferences from the decision-maker are included to generate new Pareto optimal solutions in each step. The process will finish in a non-infinite number of steps or as a satisfying solution was found, what occurs first. An example of this type of procedure is presented in Govindan, Jha, & Garg (2016). The authors deal with the design of a closed-loop supply chain for the electrical manufacturing industry. The economic dimension is evaluated through the maximization of profits. The saved costs by the recovery activities and the cost of CO_2e emissions are accounted for the environmental dimension. Finally, the social pillar is represented by a weighted sum of social indicators, including economic welfare and growth, extended producer responsibility, and employment. The proposed algorithm determines aspirational level of each objective by solving three different problems. Then a new objective function is constructed using a weighted sum of the deviations from the ideal solution to each objective. The solutions are presented to the decision-maker who decides either to stop the process and select one of the alternative solutions or to evaluate a new set of weights according to his or her preferences.

As presented below are multiple the approaches to deal with multiple objectives at assessing environmental and social performance in classics formulation of SCND. However, in the context of sustainability at supply chain level, there are some inherent problems related to the application of *a priori* and *a posteriori* methods. First, there is a difficulty of selecting the weights to cope with problems of scale, since the objectives have different magnitudes (monetary units, GHG emissions, Eco-points, lost days, jobs, and so on) (Ehrgott & Wiecek, 2005). Second, for a priori methods, it is expected from the decision maker to have some knowledge about the interdependencies of the objectives and the feasible objectives values (Hartikainen et al., 2011). However, sustainability encompasses a broad set of requirements, many of them outside of the scope of classic business decisions, and the expected results coming from the appropriation of sustainable practices might be difficult to estimate. Therefore, there is no certainty in the accurate selection of weights by the decision maker. Third, the visualization of the set of Pareto optimal solutions is not easy when the problem considers three or more objectives. Additionally, the selection of one option when a large set of solutions is displayed becomes a tough task even more when the trade-off between the conflicting objectives is not well understood (Khan et al., 2020). Last but not least, sustainability assessment is deeply linked with the definition of explicit goals, determined targets at seeking sustainable development.

That being said, the current chapter presents a *non-preference* method to the solution of MOP to the design of a supply chain network, considering economic, environmental and social criteria. Unlike *a priori* or *a posteriori* methods where the intervention of the decision-maker has a high influence on the final solution, by defining preferences over conflicting objectives. The solution method here utilized aims to minimize the maximum undesirable deviations from the best possible performance of the supply chain at every assessed dimension. The main purpose of the study is to identify the highest potential improvements achieved by the supply chain structure, while considering no bias or preferences among the objectives.

2. Problem statement

Generally speaking, this chapter addresses the design of a single-period, four-level supply chain, including production sites, processing plants, distribution centers, and retailers, as shown in Figure 4.1. The model aims to determine the optimal location and capacity of processing and distribution facilities, to choose the suppliers from a set of potential candidates, to determine transportation modes among facilities, and finally, to define the quantity of product that goes from one facility to another, in order to satisfy the demand of a product in a set of regions.

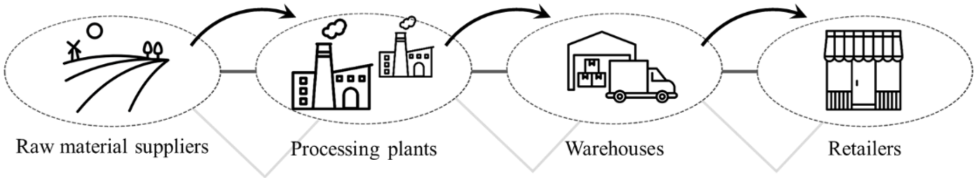

Figure 4.1. Structute of the forward supply chain

A description of the assumptions considered to the construction of the model is presented here below. Decisions on the location of plants and distribution centers in the regions are guided by two types of costs. Fixed costs, related to the capacity of the facility, are paid only if the corresponded facility is selected. Variable costs are related to the total volume of production at the corresponding facility. In our study only road transportation is available. However, given the plurality of road conditions to access farms, distribution centers in small villages, or retailers in downtown, etc., different types of trucks are considered. It is assumed that a restricted set of suitable transportation modes has been identified a priori for each supplier and retailer, considering the road characteristics. For instance, due to road conditions, such as road width, freight weight restrictions and so on, some suppliers, collection centers or retailers might present restrictions to the use of certain types of trucks. The model considers three types of trucks, namely, light truck, medium truck, and heavy truck, all conditioned for the transport of refrigerated freight and differentiated by different load capacities and consumption of fuel. The transportation cost is assumed linear in function to the quantity carried and the covered distance to each type of truck. GHG emissions are calculated by multiplying the consumption of fuel by its correspondent emission factor.

The supply chain configuration considers economic, environmental, and social factors. To evaluate the economic performance, the objective aims to minimize the total network costs, including facilities location costs, procurement costs, processing costs, and transportation costs. The environmental dimension is evaluated through the quantification of CO_2e emissions coming from production and transportation activities. Finally, the social objective is to maximize the social impact caused by the creation of employees at processing facilities and economy development through the inclusion of local suppliers. Priority has been given to less developed regions both, for the selection of suppliers and the installation of processing plants.

3. Mathematical formulation

The current section introduces the mixed-integer programming model to the design of the supply chain. The following sets are defined in constructing the mathematical model: a set of suppliers *S*, we also define a set of potential locations to install processing plants *P*, a set of potential zones to locate distribution centers *D*, a set of retailers *R*, a set of available transportation types, from farmers to processing plants *M* and from processing plants to distribution centers and retailers *T*. Moreover, Finally, *CP* and *CD* are the sets containing capacity options for processing plants *P* and distribution centers *D*, respectively. We define the following decision variables and parameters as well.

Decision variables

x_{spm}: quantity of litters of raw milk shipped from supplier $s \in S$ to processing plant $p \in P$ delivered in vehicle type $m \in M$

x_{pdt}: quantity of aggregated units of processing milk delivered from processing plant $p \in P$ to distribution center $d \in D$ by vehicle type $t \in T$

x_{drt}: quantity of aggregated units of processing milk sent from distribution center $d \in D$ to retailer $r \in R$ by vehicle type $t \in T$

y_s: equal to 1 if supplier $s \in S$ supplies any quantity of raw milk to processing plants or collecting centers, 0 otherwise.

y_{pcp}: equal to 1 if a processing plant is in potential zone $p \in P$ with capacity $cp \in CP$

y_{dcd}: equal to 1 if a distribution center is open in potential zone $d \in D$ with capacity $cd \in CD$

Parameters

We distinguish parameters in three different aspects: location, production, and transportation costs in the economic dimension.

LC_{cp}: fixed cost of opening a processing plant with capacity $cp \in CP$

LC_{cd}: fixed cost of opening a distribution center with capacity $cd \in CD$

Pr_s: Price of raw milk per ton at supplier s$\in S$

PC: processing cost per aggregated unit at processing plants

$Dist1_{sp}$: Distance in km between the supplier $s \in S$ and the processing plant $p \in P$

$Dist2_{pd}$: Distance in km between the processing plant $p \in P$ and the distribution center $d \in D$

$Dist3_{dr}$: Distance in km between the supplier $d \in D$ and the retailer $r \in R$

TC_t: transportation cost per ton of milk in transport $t \in T$

CS_s: maximum supply capacity of supplier $s \in S$

CM_{cp}: production capacity of a processing plant with capacity $cp \in CP$

Mop: maximum desired occupation rate of processing facilities

Mup: minimum allowed operation rate for processing plants

CDC_{cd}: storage capacity at distribution center with capacity $cd \in CD$

$Mudc$: minimum allowed operation rate for distribution centers

Dem_r: Demand of retailer $r \in R$

Trv_{sm}: equal to 1 if vehicle type $m \in M$ have access to retailer $s \in S$

Trv_{rt}: equal to 1 if transport type $t \in T$ have access to retailer $r \in R$

$Fcons_m$: Fuel efficiency of vehicle type $m \in M$ kilometers per gallon

$Fcons_t$: Fuel efficiency of vehicle type $t \in T$ kilometers per gallon

Cap_m: Capacity in tons of milk of vehicle type $m \in M$

Cap_t: Capacity in tons of milk of vehicle type $t \in T$

We use the following notation in referring to the environmental factors of the model

$Emfc$: CO_2e emission produced per consumed gallon of fuel

$Empr$: CO_2e emissions produced per ton of milk processed at the plant

Additionally, we use the following parameters evaluating the social performance in the social dimension

Jo_{cp}: jobs opportunities created by locating a processing facility with capacity $cp \in CP$

Ur_p: Unemployment rate at the potential location of processing plant $p \in P$

φ_s: Added value factor of the region of supplier $s \in S$

Objective functions

Assessment of impacts in social and environmental and economic dimensions are included as separate objectives in the model. The first objective equation (1) presents the total operational costs of the supply chain. This cost is the sum of opening facilities cost (i.e., processing plants and distribution centers), purchasing cost, production cost at processing plants and cost of transportation between facilities.

$$Z_1 = \sum_{p\in P, cp\in CP} LC_{cp} * y_{pcp} + \sum_{d\in D, cd\in CD} LC_{cd} * y_{dcd} + \sum_{s\in S, p\in P, m\in M} Pr_s * x_{spm} + \sum_{p\in P, d\in D, t\in T} PC * x_{pdt} + \sum_{p\in P, d\in D, t\in T} TC_t * x_{pdt} + \sum_{d\in D, r\in R, t\in T} TC_t * x_{drt} \tag{1}$$

The objective at the environmental dimension (z_2)focuses on the pollution caused by the production process and transportation. Equation (2) calculates CO$_2$e emissions emitted from transportation activities at the different tiers and the emissions coming from the processing at production plants.

$$Z_2 = \sum_{s\in S, p\in P, m\in M} \frac{Emfc * Dist1_{sp} * x_{spm}}{Cap_m * Fcons_m} + \sum_{s\in S, p\in P, m\in M} \frac{Emfc * Dist2_{pd} * x_{pdt}}{Cap_t * Fcons_t} + \sum_{s\in S, p\in P, m\in M} \frac{Emfc * Dist3_{dr} * x_{drt}}{Cap_t * Fcons_t} + \sum_{s\in S, p\in P, m\in M} Empr * x_{pdt} \tag{2}$$

In the model two different factors represent the social dimension. The first one, to maximize the social benefit associated with the generation of employment in the zone of located processing plants. The second one, to maximize the social benefit associated with the selection of local suppliers. These two objectives are evaluated together in a normalized equation (3). The denominator of each term in the equation is a sum of parameters representing the maximum possible value to obtain. For instance, $\sum_{s\in S} \varphi_s$, corresponds to the sum of add value factor for all regions of suppliers $s \in S$, so each term in (3) becomes in a percentage respect to an upper bound of it itself.

$$Z_3 = \frac{\sum_{p\in P, cp\in CP} Ur_p * y_{pcp}}{\sum_{p\in P} Ur_p} + \frac{\sum_{s\in S} \varphi_s * y_s}{\sum_{s\in S} \varphi_s} \tag{3}$$

Constraints

Demand and flow conservation constraints

Equation (4) ensures that the retailer's demand is met. Equations (5) and (6) guarantee the flow balance at processing plants and distribution centers, respectively, by equating the total inputs and outputs at each type of facility. To avoid unrealistic results when considering the social dimension, equations (4), (5) and (6) are defined as equalities. As an example, if demand is not established as an equality, the model in the third scenario could lead to an overflow production seeking to create a large number of employees, resulting in an unrealistic operation.

$$\sum_{d\in D, t\in T} x_{drt} = Dem_r \qquad \forall\, r \in R \tag{4}$$

$$\sum_{s\in S,m\in M} x_{spm} = \sum_{d\in D,t\in T} x_{pdt} \qquad \forall\, p \in P \tag{5}$$

$$\sum_{r\in R,t\in T} x_{drt} = \sum_{p\in P,t\in T} x_{pdt} \qquad \forall\, d \in D \tag{6}$$

Facilities capacity constraints

$$\sum_{p\in P,m\in M} x_{spm} \le CS_s * y_s \qquad \forall\, s \in S \tag{7}$$

$$\sum_{d\in D,t\in T} x_{pdt} \le \sum_{cp\in CP} CM_{cp} * y_{pcp} * Mop \qquad \forall\, p \in P \tag{8}$$

$$\sum_{r\in R,t\in T} x_{drt} = \sum_{p\in P,t\in T} x_{pdt} \qquad \forall\, d \in D \tag{9}$$

Constraint (7) limits the total amount of raw milk shipped from supplier s ∈ S to processing plants p ∈ P to the capacity of each supplier. Constraint (8) establishes bounds for the quantity of production at each opened processing plant. Constraint (9) ensures that the capacity of the distribution center is not exceeded.

Transportation availability

$$\sum_{p\in P} x_{spm} \le CS_s * Trv_{sm} \qquad \forall\, s \in S, m \in M \tag{10}$$

$$\sum_{d\in D} x_{drt} \le \sum_{d\in D,cd\in CD} CDC_{cd} * y_{dcd} * Trv_{rt} \qquad \forall\, r \in R, t \in T \tag{11}$$

Constraints (10) and (11) ensure the delivery of raw milk and processed products only in available vehicles according to the restriction of access for each supplier and retailer, respectively.

Operational constraints

Addressing environmental and social assessment without operational conditions aspects would drive into not realistic solutions (Brandenburg, 2015). Moreover, one of the critical factors in the social field of corporations is to be profitable; a profitable company is able to offer stable working conditions, contributes to the development of the region while satisfying the demand in the market. Hence, this model considers some minimal operational requirements expressed in the following constraints.

$$\sum_{d\in D,t\in T} x_{pdt} \ge \sum_{cp\in CP} CM_{cp} * y_{pcp} * Mup \qquad \forall\, p \in P \tag{12}$$

$$\sum_{d\in D} x_{pdt} \ge \sum_{cd\in CD} CDC_{cd} * y_{dcd} * Mudc \qquad \forall\, d \in D \tag{13}$$

$$\sum_{cp\in CP} y_{pcp} \le 1 \qquad \forall\, p \in P \tag{14}$$

$$\sum_{cp\in CP} y_{dcd} \le 1 \qquad \forall\, d \in D \tag{15}$$

To avoid the creation of employees on idle processing plants, constraint (12) ensures that an open processing plant is used at least at its minimum balance capacity. In the dairy sector processing plants used to be constructed with a recognized overcapacity to attend fluctuations in the processing of raw milk in rainy months. Use a plant at partially capacity might be acceptable. Same way, constraint (13) imposes a minimum use of the capacity for open distribution centers. Constraints (14) and (15) limit to one the number of processing plants or distribution centers open at each selected region, respectively.

4. Solution approach

For the solution of the multi-objective optimization problem (MOP) defined in the previous subsection, a Chebyshev goal programming is proposed to find a balance between the accomplishment of the objectives. Chebyshev goal programming can be considered as a specific form of the weighted goal programming (Thill, 2019). A set of single goal optimization problems are solved to arrive at the best and worst possible values of each objective. The best values are then used as the upper bounds or the aspiration levels for the objectives. The objective becomes one of minimizing the differences from those aspirational levels, so the solution obtained minimizes the worst unwanted deviation from any single goal (Ghufran et al., 2015). To apply the Chebyshev goal programming approach to the solution of the MOP, a new set of constraints need to be added (16). Let O be the value of an element of the set of the multiple objectives to be evaluated, $O \in \{z_1, z_2, z_3\}$, and let n_O and p_O be the negative and positive deviation of the objective O from its target value O_{target}, then:

$$O + n_o - p_o = O_{target} \; \forall O \; \in \; \{Z1, Z2, Z3\} \tag{16}$$

The Chebyshev goal programming variation aims to minimize the maximum undesirable deviations from the defined target for any single objective. In our specific case, since both economic and environmental objectives correspond to a minimization function, favorable variations are undesirable for these objectives, while a negative deviation is undesirable for the social objective. Let Z_1^*, Z_2^*, Z_3^* be the ideal values for the economic, environmental, and social values, respectively, and let p_{Z1}, p_{Z2}, and n_{Z3} the undesirable deviations for each objective. For instance, as a rise in the total cost is an undesirable result to the economic dimension the positive deviation appears in the relation. While n_{Z3} appears in the equation related to the social objective since here a negative deviation represents a low social impact. Finally, let λ be a scalar representing the percentage deviation of each objective to the intended solution. Therefore, constraints (17)-(19) are added to the model, and (20) become the new objective function to be addressed.

$$\frac{p_{Z1}}{\mathrm{Z}_1^*} \leq \lambda \tag{17}$$

$$\frac{p_{Z2}}{\mathrm{Z}_2^*} \leq \lambda \tag{18}$$

$$\frac{n_{Z3}}{\mathrm{Z}_3^*} \leq \lambda \tag{19}$$

$$min\ \lambda \tag{20}$$

5. Case study

The case described in this section is based on a realistic supply chain aiming to serve the demand for milk and dairy products in the central region of Colombia. Economic, environmental, and social data for the case study were obtained with Colombian data through sectoral entities, previous studies from governmental agencies, and sustainable reports of milk processing industries when possible. Regarding investment cost for the construction of new facilities, production plants or warehouses, it is estimated by considering the price of similar facilities that is already built. The milk processing plant in Santa Marta (Colombia) with a capacity 20 million liters/year and an investment of USD $4.8 million in 2015 and the plant in Arauca that process about 11 million liter/year and its cost was USD $2.63 million in 2020. For warehouses, the investment is based on distribution centers owned by milk processing companies: 12000 square meters with an investment of about USD $ 11 million in 2016. Values are presented at the average Colombian COP exchange rate of USD in 2018.

Environmental data for calculating impact caused by both, milk transportation and milk processing were obtained through a specific excel-based tool for Colombian fuels constructed by the Colombian Mining and Energy Planning unit[1] and the revision of sustainability reports of milk processing plants, respectively. Regarding the production process, both, scope one direct emissions for fuel combustion and fugitive emissions and scope two indirect emissions for purchasing electricity, heat, and steam are included. Finally, Colombian national statistics were considered to get data in the social dimension, unemployment rate and the percentage share of each municipality in the national GDP served as factors for the classification of the of regions regarding economic development.

In usual operation of the supply, processing plants receive raw milk coming directly from farms or from milk collection centers. The latter serves as a hub for the consolidation of milk coming from small dairy farms. It is worthy to note that since the model focuses on the strategic and tactical decision in the supply chain, routing plans to collect milk from different farms to collection centers are out of the boundaries of the study. Once at processing facilities, raw milk is pasteurized and homogenized to extend shelf life of milk and to ensure product quality. There, several dairy products are packaged, and some quality tests are applied before shipment approval. Although processed milk and other several dairy products such as yogurt, cream, cheese, and whey are produced and transported through the network, to simplify the mathematical formulation, we consider a single aggregated unit for the product going for farms to retailers (i.e., equivalent tons of milk), so different dairy products might be represented by their contain of milk. After processing, different types of milk and dairy products are shipped from the processing plants to the different distribution centers (DC's). Finally, the products are sent to retailers to meet demand in the market.

6. Results

As mentioned above the definition of target values for every objective constitute the first step in performing Chebyshev goal programming. To this regard, three separated linear programming models were executed without regard to the remaining two objectives. Experiments are run using GAMS (General Algebraic Modeling Systems) with the MIP solver ILOG CPLEX 12.2. The experiments were conducted on a PC

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[1] The database is available at http://www.upme.gov.co/Calculadora_Emisiones/aplicacion/calculadora.html

with processor Intel Core i5 4200U, 1.60 GHz and 8.00 GB of RAM. The computational time for the problem is negligible, and therefore, no analysis will be done in this regard. Results from these experiments are shown in Figure 4.1. The first column of the table shows the three different objectives to be evaluated that correspond to equations (1), (2), and (3), respectively. In front of each one of them, columns 2, 3, and 4 present the respective associated value for the remaining sustainability dimensions. The second column shows the total cost of the configuration in thousands of millions COP. The total emissions in CO_2 eq. tons are presented in column 3. The fourth column of the table presents the results for the social dimension, the objective function value (*at the top*) (i.e., social impact factor) as well as the number of created jobs and the number of contracted suppliers in each configuration (above).

Table 4.1. Results for single objective linear programming models

	Sustainability performance indicators			
Optimizing objective	Total cost (COP ‘000M)	CO_2 emissions (Ton)	Jobs quantity	Suppliers
(1) Economic objective	**278.7***	46,015	0.994	
			130	19
(2) Environmental objective	297.1	**44,513***	1.024	
			130	24
(3) Social objective	279.8	47,633	**1.28***	
			130	23

*****Ideal value for every objective

From Table 4.1, it is worthy to note the trade-offs between the different objectives. Slightly variations are presented in each one of the single objective scenarios analyzed. The network configuration aiming to minimize the total amount of CO_2 emissions is about 7% more expensive than the best option and presents a reduction of only 3% in the CO_2e emissions level that it. The difference in these costs is mainly caused by the number of distribution centers in each network structure. Although only one milk processing plant is open in each one of the different models, the model focuses on cost minimization accounts with two distribution centers of large capacity in zone 1 and zone 6, meanwhile the model with the environmental objective consists of four facilities at this level, two small capacity distribution centers in zones 4 and 6, one medium capacity distribution center in zone 1 and one distribution center of large capacity in zone 3.

Figure 4.2 presents a distribution of the drivers of cost for each one of the independent single-objective optimization problems. Production cost remains the same in every configuration. Small differences are observed in the procurement cost and transportation cost, while the cost of locations of facilities presents the most notable difference, particularly, to the reduction of GHG emissions.

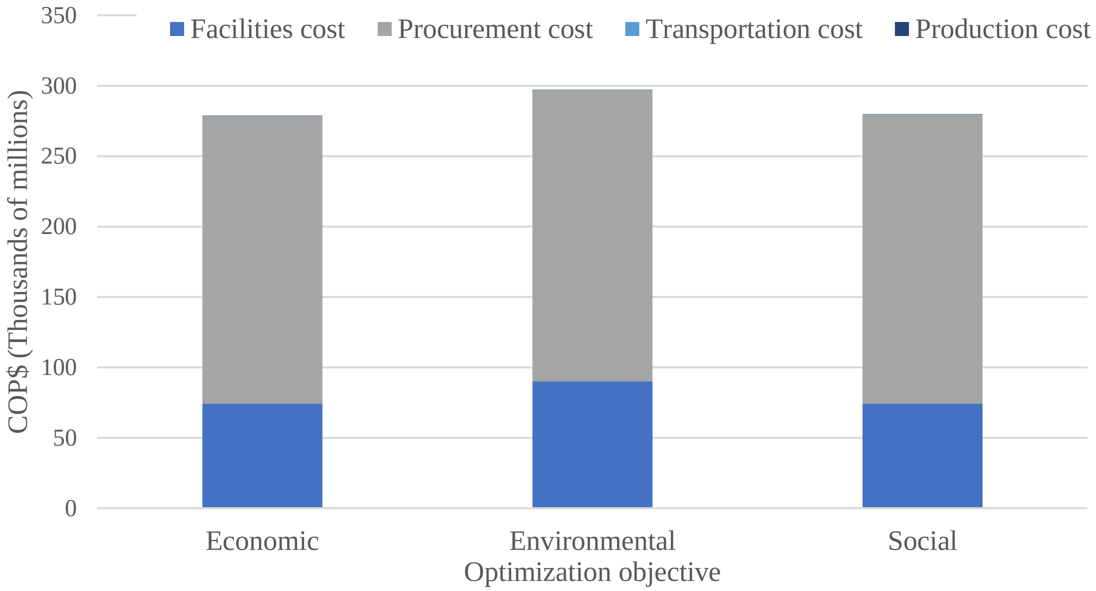

Figure 4.2. Cost drivers for the individual objectives

It is also noted that the cost for the configuration guided by the social objective is very similar to the optimal one, in fact, it is just above 0.3% greater, but the level of CO_2e emissions is the highest among the evaluated possibilities. In fact, even when transportation costs in the scenario guided by the social objective increase just about 8% in comparison with the scenario guided by the environmental function, the level of emissions grows about 84%. Figure 4.3 presents a comparison in the level of CO_2 emissions generated by transportation activities between suppliers and plants, plants and DC’s and DC’s and retailers for the three different single objective problems. The first scenario favors the location of a smaller number of processing plants, which increases the total number of kilometers traveled from farms to processing facilities, which is reflected in the notable contribution to the CO_2 emissions in this link. Conversely, the opening of more processing plants favors the reduction of emissions from transportation in the second scenario.

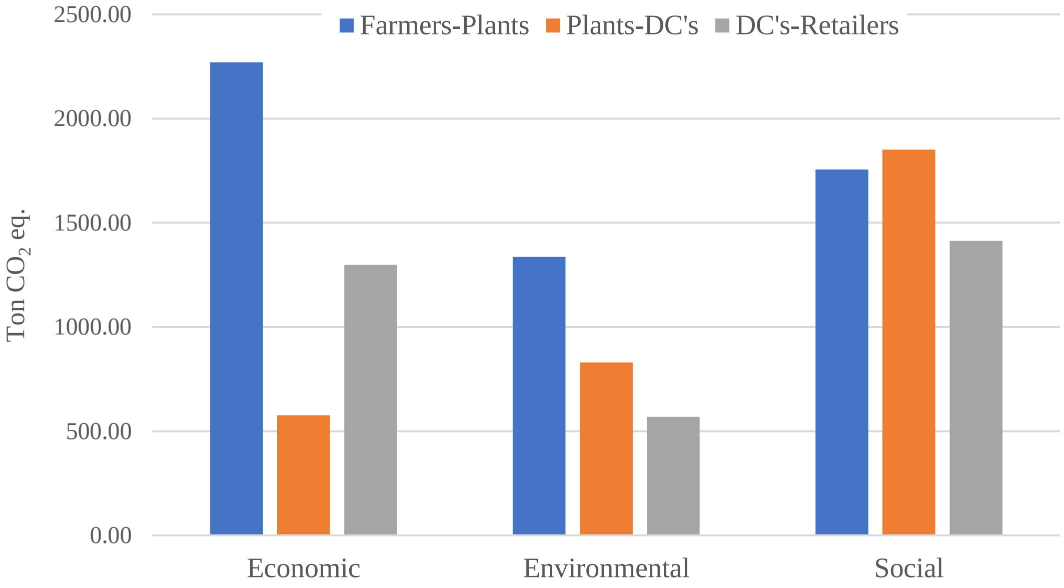

Figure 4.3. CO_2eq emissions for transportation activities at different tiers

In the third scenario guided by the social objective, the number of tons of CO_2 derived from transportation activities increases considerably, mainly due to the transport of products between the production plant and the distribution centers. The reason is that in this scenario the decision regarding the location of processing plants and the selection of suppliers privileges the areas with the least development and the highest unemployment rate, which usually corresponds to those areas remote from large consumption centers and challenging access routes. On the other hand, as also shown in Table 4.1, for all network configurations, the number of created jobs is the same: a processing plant of small capacity that requires 130 new employees.

Interestingly, although the optimization of the social dimension has negative impacts on the environmental performance measure as described before regarding the number of emissions, this does not occur in the other way around. In fact, the scenario guided by the environmental objective has a higher number of suppliers and reaches a social impact measure about 20% under the optimal. The main difference affecting the result on the social value indicator is the region in which the milk processing plant is installed and the region of the selected suppliers. While in the first case (i.e., environmental objective model) they are selected according to the minimum travel distance and the availability of use greener transportation means to cause the least number of emissions, in the second case (i.e., social performance objective) they are selected prioritizing the areas with the lowest economic development. So, although the number of suppliers is higher in the scenario optimizing the environmental impact, the distribution of selected suppliers in the social scenario presents better performance.

Table 4.2. Summary of the network structure for each independent model

Objective function	**Suppliers**			**Processing plants**				**Distribution Centers**					
	F1	F2	F3	P1	P2	P3	P4	C1	C2	C3	C4	C5	C6
Z_1	14	2	3			S		L					L
Z_2	13	6	5				S	M		L	S		S
Z_3	17	4	2	S				L	L				

Table 4.2 presents a summary of the results specifying the number of suppliers by zone and selected location for opening processing plant and distribution centers. To avoid a more massive extension of the table suppliers are divided into three different categories according to its value-added parameter (φ_i). Let F1 be the set of suppliers with the lowest values, $F1 = \{s_i \mid 0.1 \leq \varphi_i \leq 0.8\}$, $F2 = \{s_i \mid 0.8 < \varphi_i \leq 1.5\}$, finally, suppliers located in regions with the highest value are grouped in set 3 $F3 = \{s_i \mid \varphi_i \geq 1.5\}$. Moreover, potential facility locations for processing plants are listed from P1 to P4, being P1 the potential location with the highest unemployment rate, P2 the second and so on. The first column of Figure 4.2 presents the objective function evaluated in the model. Columns two, three and four, present the number of suppliers at each category, Then, in column five to eight the potential location for processing facilities. We use the letter S from small, M from medium and L from large to present the capacity of the processing plant at the selected location. The same convention is used to describe the capacity of installed distribution centers in the six potential locations.

Chebyshev goal programming approach

Due to slight variations in different configurations of the SC, a non-weighted Chebyshev goal programming is used to balance the economic, environmental, and social objective in the problem under study. After defining, the target Z_1^*, Z_2^*, and Z_3^* from the optimization of individual objectives in section 3. The Chebyshev goal programming is performed as described in section 4. From the execution is possible to note that there does not exist a configuration in which all objective targets are met without deviation. So, different trade-offs are presented in the new structure of the supply chain. Results of the execution are shown in Table 4.3. The first and second column present the objective and its related target, in the third column is presented the deviation respect to the target value with a plus sign (+) if it corresponds to a positive deviation or minus sign (–) if it corresponds to a negative deviation. Finally, the last column presents the percentage of variation for each objective and the value of lambda in bold.

Table 4.3. Results of Chebyshev goal programming

Objective	Target	Calculated deviation	λ (%)
Z_1	2.787E+11	(+) 1.017E+10	3.61
Z_2	44,513	(+) 1,780.55	**4.01**
Z_3	1.28	(-) 0.044	3.44

Variations are presented for all objectives — the largest of these regarding the environmental issue. The new structure of the supply network has an increase of 4% in the level of CO_2e emissions above the desired value for this objective. Is worthy to note how this value is higher than the emission caused in the scenario guided by the economic function and allows us to see the complexity of the relationship between environmental and social objectives. In fact, this solution prioritizes the social performance of the supply chain. Regarding the structure, 16 suppliers from the least developed regions are selected, and the processing plant is also installed in the region with the highest unemployment rate. Three distribution centers are open: one small capacity distribution center in zone 4, one medium capacity distribution center in zone 2 and on a large capacity distribution center in zone 6. Summary of the structure of the network given by goal programming is presented in Table 4.4

Table 4.4. Structure of the supply chain Chebyshev goal programming

Objective function	**Suppliers**			**Processing plants**				**Distribution Centers**					
	F1	F2	F3	P1	P2	P3	P4	C1	C2	C3	C4	C5	C6
GP	16	1	3	S					M		S		L

It is possible to observe how a reduction of emissions of CO_2e requires an economic effort. Moreover, we highlight the relation between environmental and social performances; the pursuit of better results in social performance ends up affecting the environmental performance of the distribution network. One of the significant factors is the unavailability of efficient roads to transport products from isolated regions. Herein lies the relevance of defining objectives to the sustainable key indicators. The definition of preferences by the decision maker can lead to good solutions, however, even when these solutions mean an improvement over the current company situation, in a broader view, might remain unsustainable in reference to the social and environmental objectives of the sector or the country.

7. Conclusions

This chapter presented a multi-objective optimization model incorporating the three dimensions of sustainability for supply chain network design. The model addressed explicitly with strategic and tactical decisions while considering the minimization of the total costs (economic dimension), the minimization of CO_2e emissions at both processing facilities and transport (environmental dimension), and two factors in the categories of work conditions and societal development (social dimension). Aiming to balance the solution without the inherence of bias or decision-maker preferences, this chapter presents a Chebyshev Goal Programming method, intended to balance the undesirable deviations of ideal points for every single objective.

A case-study research in the dairy sector of the central region of Colombia was taken as an exemplary application. The results evidence trade-off among economic, environmental and social objectives. The defined targets are ambitious in itself. The unweighted balance results give more priority to the social dimension, which obtains the least deviation, thus affecting the environmental performance of the chain. In regard to the proposed approach for supply chain design under sustainability metrics, decision-makers will have at hand a set of possible configurations to be chosen in order to comply with environmental and social regulations without neglecting economic performance. Indeed, the agro-industrial sector is prone to high impacts of supply chain and logistics decisions in terms of social and environmental performance, and so the dairy sector of emerging economies, in particular.

Results show how location and allocation decision might have an impact on sustainable development. However, it pops up different inquiries, for instance, although new supply chain structure could entail GHG emissions savings, question might be how much improvement is needed to consider the new structure as sustainable? Moreover, since most of the works address the evaluation of already constituted supply chain, how long it takes to go from the actual structure to the desirable structure? These questions are related with the definition of sustainable development and highlight the importance of the definition of objectives at assessing sustainability in any system. Following chapters address these previous questions at considering multi-period models to exemplify the execution of activities in the long-term leading to a stable state in the sustainability indicators of the chain. National and continental plans to the reduction of GHG emissions and the improvement of social health and living conditions are consider to the definition of goal for every sustainability dimension. Besides, a wider view of sustainability is analyzed at considering supply chains as part of community development.

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Chapter 5 Case Study Description

The current chapter presents a description of Colombia's dairy sector, considering its implications to the economy, environment, and society. We present a general description of the agricultural sector at national level. It highlights the relevance of the livestock sector for the society and the environment. Particularly, we present logistics, environmental and social conditions in the dairy industry. We highlight the most significant sectorial challenges nowadays, to lead a sustainable transformation. Addittionaly, we present a summary of the long-term sustainable objectives in the supply chain network design model in line with the sectorial development plans. Finally, we list plausible external scenario drivers, according to the existent long-term development policies in the sector.

1. Colombian Agricultural sector

Colombia is located in northwestern South America (see Figure 5.1). It borders Ecuador, Peru, Brazil, Venezuela, the Caribbean Sea, Panama, and the Pacific Ocean. Colombia is the 26th largest country in the world, with an area of about 1,138,914 km^2 and 50.34 million inhabitants by 2019. It comprises 32 departments and the Capital District of Bogota. The climate of Colombia is mainly tropical, presenting variations within six natural regions, characterized by differences in altitude, temperature, humidity, winds, and rainfall, because of a three-branched subdivision of the Andes mountain range. Its territory encompasses Amazon rainforest, highlands, grasslands, and deserts. The rainy season is bimodal, being from April to June and from August to November. However, precipitation levels also vary widely within the country: The eastern Caribbean coast is impoverished in rainfall with less than 400 mm of rainfall per year, while in the west of the Andes, there are up to 16,000 mm of precipitation per year in some areas. This diversity of factors determines the potential of soils for a wide variety of agricultural activities.

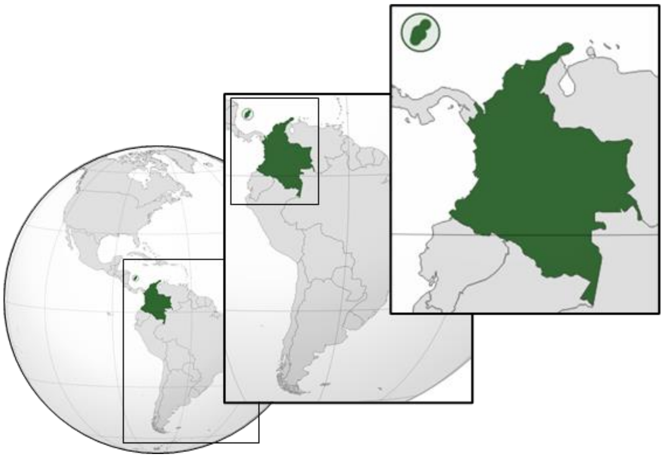


Figure 5.1. Case study location
Source: Modified from COL Orthographic. License: CC BY-SA 3.0

Agriculture has historically been one of the main engines of economic development in Colombia. Given its vast natural resources, diverse climate, and varied topography, agricultural business opportunities are abundant in the country as the potential role of Colombia as a global supplier continues to grow. The sector is supervised by the Ministry of Agriculture and Rural Development (MADR). Its central objective is to formulate, coordinate, and evaluate policies that promote competitive, equitable, and sustainable development of agricultural, forestry, fisheries, livestock, and rural development processes. Agriculture represents about 6.7% of the national GDP and accounts for over 20% of the national employment by 2019. Over the past five years, the sector has shown a slight and steady increase, to some extent due to the peace agreement that ended an internal armed conflict that lasted more than half a century. This peace has brought agricultural, and other economic interests to previously undeveloped rural areas and has raised concerns about the need to protect environmental biodiversity.

In 2018, after almost five years of cooperative work between MADR, the Colombian Ministry of Environment and Sustainable Development (MADS), and The Agriculture planning unit (UPRA), the national agriculture frontier was defined for the first time (UPRA & MADR, 2017). The document defines rural land boundary separating areas where agricultural activities are carried out from protected areas and other strategic ecosystems where agricultural activities are excluded by law. It aims to develop land formalization programs in areas with the aptitude to advance long term sustainable productive projects. It is a tool for coordinating competitive agricultural enterprises with the protection of biodiversity.

According to UPRA & MADR (2017), the Colombian national agriculture frontier includes about 36 million hectares, representing nearly 32% of its continental territory. There the development of agricultural, livestock, forestry, aquaculture, and fishing activities are allowed. Nowadays, about 50 million hectares are occupied with some sort of agricultural activity. About 5 million hectares are croplands, while about 39 million hectares correspond to grasses and fodder, mostly occupied for livestock husbandry. The remaining area is occupied with forest and other uses of land. One of the main challenges is to reduce land use conflict of agricultural activities in environmental protection territories, namely, forest reserve areas, moors, and national parks.

As reported by IDEAM (2018), historically, Agriculture, Forestry, and other land use (AFOLU) have been the most significant GHG emissions source in Colombia. From 1990 to 2014, the AFOLU sector has represented about 65% of the total national GHG emissions. However, the marginal contribution of AFOLU has been progressively decreasing over time, going from 77% in 1990 (158.02 Gg CO_2 eq.) to near 55% in 2014 (129.51 Gg CO_2 eq.), while total national emission has increased by only about 9.6%. As presented in the Colombian national GHG inventory in Figure 5.2, livestock activities account for around 40% of the GHG emissions within the AFOLU sector, mainly due to enteric fermentation, manure management, and forest land converted to pastures.

From the above description of the agricultural sector in Colombia, at least two notable facts emerge. On one hand, the potential of the country to become a global pantry without compromising environmental biodiversity, due to the wide availability of resources, but the imminent necessity of the reorganization of productive systems. On the other hand, the significant role of the livestock sector in the country and its influence on society and environmental development.

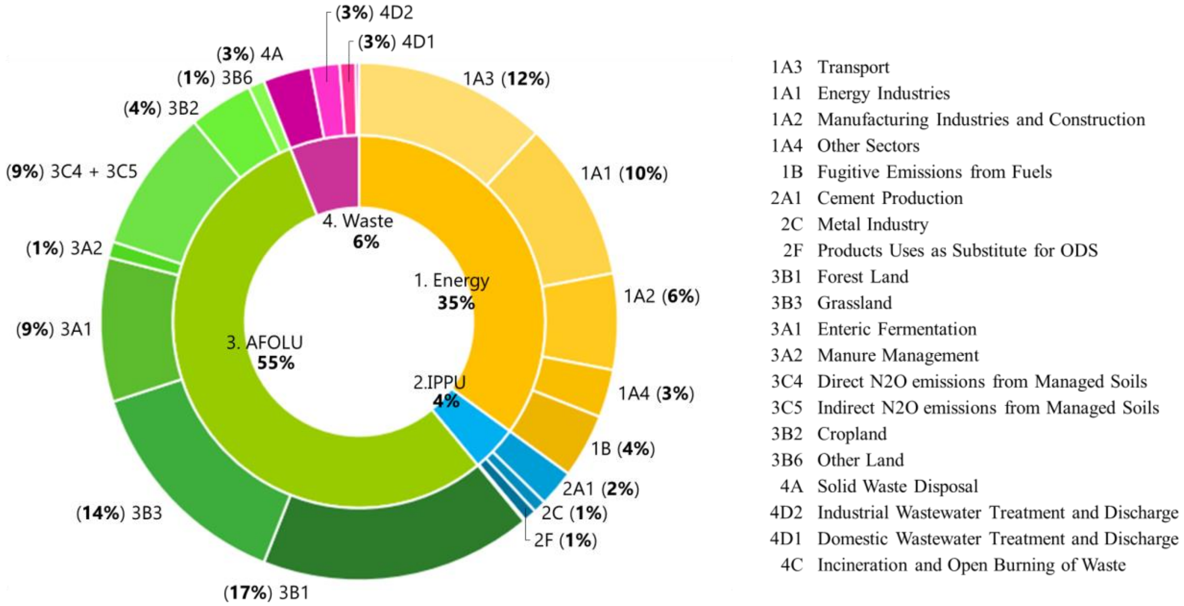


Figure 5.2. Colombian greenhouse gas inventory by 2014
Data source: (IDEAM, 2016)

2. Colombian dairy sector

Colombia is currently the fourth-largest producer of milk in Latin America, excelled only by Brazil, Mexico, and Argentina. The dairy sector in Colombia gathers more than 400,000 productive units, generates about 900,000 direct jobs in milk production and more than 15,000 in the dairy processing industry. It also has an essential share in the country's economy, representing about 25% of the livestock sector's gross domestic product and near 12% of the total agricultural GDP. National production of milk has presented a constant rise during the last decade, mainly by increasing the livestock inventory and the expansion in the number of productive units of farms within the post-conflict context. Nowadays, Colombia produces around 7.19 billion liters of milk per year. However, only about 50% of this production goes to the industrial stage of the chain. The remaining milk production is sold in informal markets, usually in the surrounding regions of producing farms. Considering national milk production capacity and the recent free trade agreements signed by the United States, The European Union, and other Latin American countries, Colombia could become a significant exporter of dairy products. However, lack of processing capacity, low competitiveness in terms of animal productivity, and the sector's price regulation have been barriers to this objective (Cadena et al., 2019).

For presenting what formal and informal markets mean in the case study context, it is prompt to mention some Colombian dairy sector regulations. One of the central policies applied to the sector address the definition of minimum sold price per liter of milk (Cadena et al., 2019). The price framework began with resolution 012 of 2007 and was modified years after by resolution 017 of 2012 of the Colombian Ministry of Agriculture and Rural Development. To strengthen the market supply with quality dairy products in a competitive process, the ministry defined a formula to calculate the price of a liter of raw milk considering its protein and fat content in grams per liter. Additionally, bonuses or discounts affect the final price of milk. For instance, the hygienic production of milk bonus, based on the estimated number of viable bacteria per ml of milk (colony-forming unit/ml), or cattle health quality bonus, considering the foot-and-mouth disease or brucellosis-free register. Finally, voluntary bonuses from the buying agent are considered. Discounts are also made explicit according to the type of transport. The resolution establishes the transportation cost according to the distance in kilometers to the round-trip from the processing plant to the farm or the collection point. Thus, the resolution specifies the amount of money per liter that must be discounted according to the distance and transport vehicle type.

Every buying agent, namely, intermediary or milk processing company, are compelled by the current regulations to execute every purchase according to the specification in the resolution and to report the purchase to the milk price monitoring unit (USP), including purchased volume, the price paid per liter, register of protein, fat and solids content in milk and bacterial levels by an authorized laboratory. Milk purchases meeting the regulatory requirements belong to the *formal market*. On the contrary, purchases executed out of the regulation criteria classify as transactions in the *informal market*.

Figure 5.3 shows the destination of the national production of milk in 2019, considering the formal and informal market and the agents involved in the transaction. According to USP, around 47% of the national production of milk was collected by the formal market, directly by milk processing industries, or through intermediaries, which correspond to associations of cooperatives of small and medium farmers that join seeking better negotiation conditions. About 7% is consumed on farms, and the rest of it goes to the market through non-formal agents.

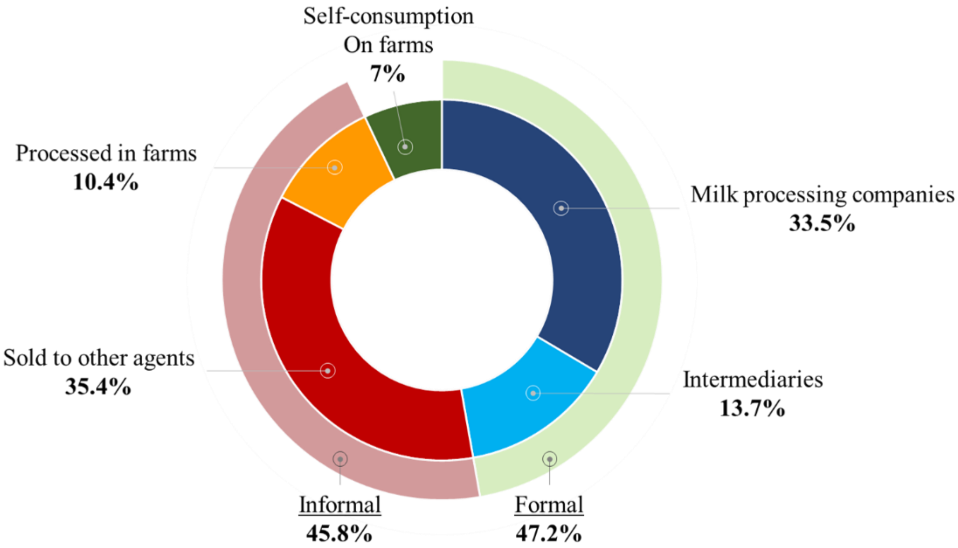


Figure 5.3. Destination national production of milk per year in 2019
Data source: FEDEGAN 2020

Although informality varies from one region to another, it is more prevalent in remote rural areas with smallholders' extended presence. According to (Bridge, 2015), there are different conditions linked to producers in informal markets. Informality is related to low incomes since raw milk is paid at lower prices than the one defined by the Ministry of Agriculture and Rural Development on the formal market, which derives from low wages and informal labor. Informality is also related to low hygienic production practices because of a lack of cooling systems, deficient access to electricity distribution networks, and rudimentary collecting practices. Mainly factors promoting informality include difficult access to rural zones due to poor road infrastructure, high dairy products prices in the formal channel, lack of business vision and cooperation between smallholders, and the notable difference between production and processing capacity dairy sector. Succinctly, the high informality in the sector is one of the conditions that threaten the sustainable development of the industry. Farmers are paid less than they deserve, less to cover at least their own production costs. Processors compete against products with unfair prices, and consumers are exposed to products that, in some cases, do not meet safe and healthy regulations.

Figure 5.4 presents the general structure of the Colombian dairy supply chain, including its primary stages, expressly, production, collection or transportation, processing, and distribution. Noteworthy, the model considers activities exclusively on the formal channel. It involves the whole national production of milk and the total consumption through the apparent milk consumption, calculated by adding the national production and the imports, minus the exports. Since there is a direct link between formal collection and the processing industry, meaning that all milk collected in the formal channel end up in the formal processing industry, we consider a four-echelon supply chain including production, processing, distribution, and consumption.

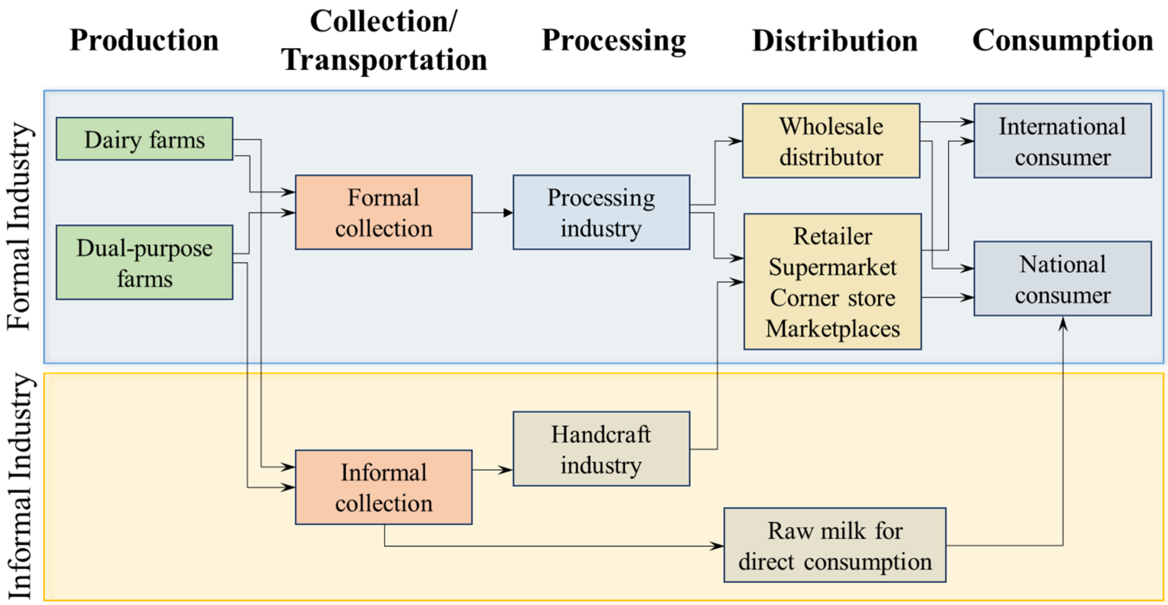


Figure 5.4. Structure of the Colombian dairy supply chain
Source: National Dairy Council

Production

The production stage is mostly composed of small farmers, characterized by low production rates and low incomes (FEDEGAN, 2013). As presented in Figure 5.5 from the property structure study results carried out by the Colombian Agriculture Institute ICA (FEDEGAN, 2018), about 40% of the productive units have less than ten animals. Almost 67% of the farms have less than 25 animals. This population often lives in remote rural areas, get limited access to health care systems, education, and technology. Cash flow provided by the sale of milk, low barriers to access to markets, and the high nutritional value of milk result attractive for a large group of smallholders who get their familiar livelihood from there. Within this range, the smallholder milk production can be considered as a subsistence activity or emerging farming.

Additionally, around 31.5% of the farms have between 26 and 500 animals per farm, including emerging and profitable businesses. Only 1% of the farms can be considered high-scale production with more than 500 animals per productive unit. As presented by (MADR & UPRA, 2018), the smallholders with up to 25 animals per farm produce about a quarter of the national milk production. The most prominent farmers contribute only around 9% of it.

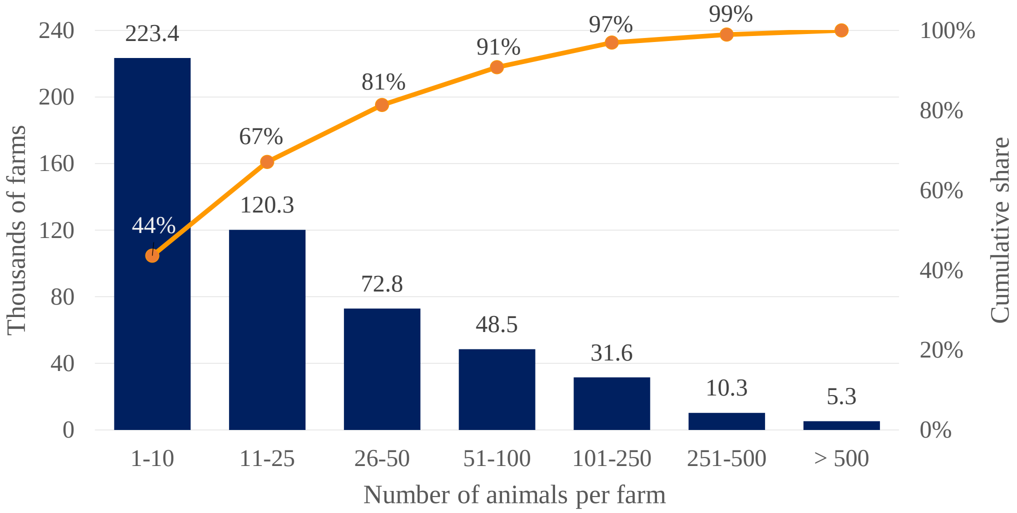


Figure 5.5. Livestock farms size in Colombia
Data source: FEDEGAN 2018

In the country, out of the six natural regions, five have the potential for meat and milk production. Not surprisingly, there is a register of milk farms in 1104 out of the 1122 municipalities conforming to the country (MADR & UPRA, 2018). Although, as mentioned before, the regions differ in temperature, rainfall and so on, they are often classified into two different categories: tropical highlands and tropical lowlands, according to some climate variables as presented in Table 5.1. These variables significantly impact the availability and quality of pastures, animal productivity, land cost, and other essential production variables.

Table 5.1. Classification of land in Colombia according weather and soil conditions
Source: (Reyes, N.D)

Climate variable	**Tropical Lowlands**	**Tropical Highlands**
Temperature	> 22°C (72°F)	< 14°C (57°F)
Precipitation	< 800 mm (31in)	600 to 2600 mm (24 to 102in)
Altitude	4 to 1250 m.a.s.l.	1750 to 4200 m.a.s.l.
Soil type	Alkaline and sodic soils	Acid soils, volcanic slabs

Hence, milk production comes from two different production systems: the specialized dairy system and the dual-purpose system. The former is exclusively dedicated to milk production, whereas meat and milk are produced in the latter. Specialized dairy farms are mainly located in highlands regions and usually close to urban centers. About 80% of dairy farms in highlands are exclusively oriented to milk production. In these regions, specialized dairy cattle husbandry, quality, and pasture availability, besides concentrate feed, allow reaching production rates between 12 and 15 liters per animal per day. In comparison, these values barely reach between 4 and 6 liters per animal per day in lowlands. Specialized dairy systems present higher levels of productivity (i.e., liters of milk/animal), higher animal load (i.e., animals/hectare), higher production cost ($/liter of milk), and better milk properties (i.e., fat and protein content) as well, in comparison with dual-purpose systems.

On the other hand, dual-purpose systems prevail in tropical lowlands. In this system, farmers use tropical cattle breeds crossed with dairy breeds, having the opportunity of producing meat, milk, or both depending on market conditions. When the price of milk is high, milk is commercialized; otherwise, milk is used to feed calves for meat production. From an economic and social perspective, dual-purpose systems are desirable to small and medium scale with reduced resources and low milk productivity, as the income for selling milk is used as a financial resource to support the long payback times on meat farms (FEDEGAN, 2018).

As shown in Figure 5.6, out of the nearly 27 million heads of bovine cattle, about 12 million contribute to milk's national production, which represents about 41% of the total livestock inventory by 2019. Despite the lower productivity rate per animal in dual-purpose systems, these farms contribute about 55% of the total national production of milk because of the number of animals they concentrate on. The remaining percentage of production comes from high productive animals in the specialized dairy system.

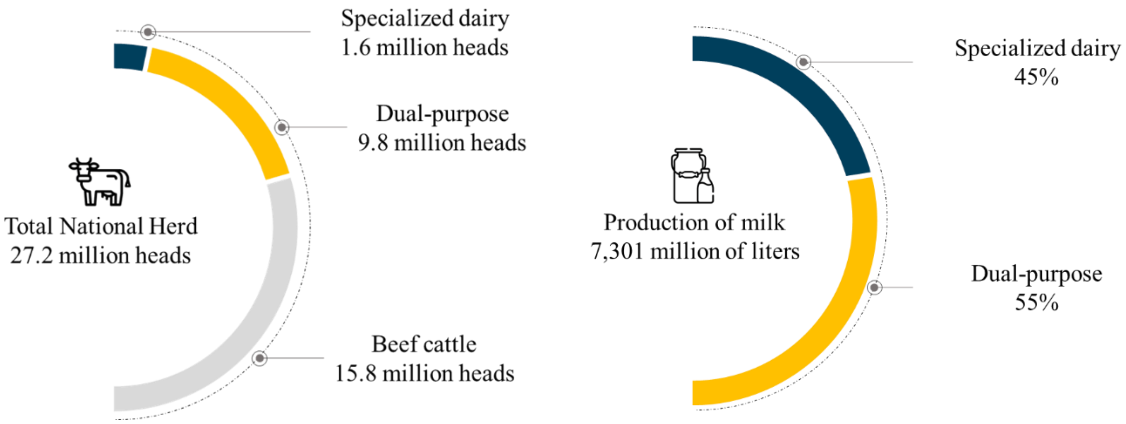


Figure 5.6. National livestock productive orientation and milk production in 2019
Data source: FEDEGAN, 2019, UPRA 2019

During the last decade, milk production has grown by 1.6% on average per year, as shown in Figure 5.7. It had a remarkable recovery over the last three years, after the devastating consequences of the El Nino phenomenon during 2015 and 2016, which caused 40 thousand animal casualties and more than 700 thousand displaced animals due to flooding of fields and pastures.

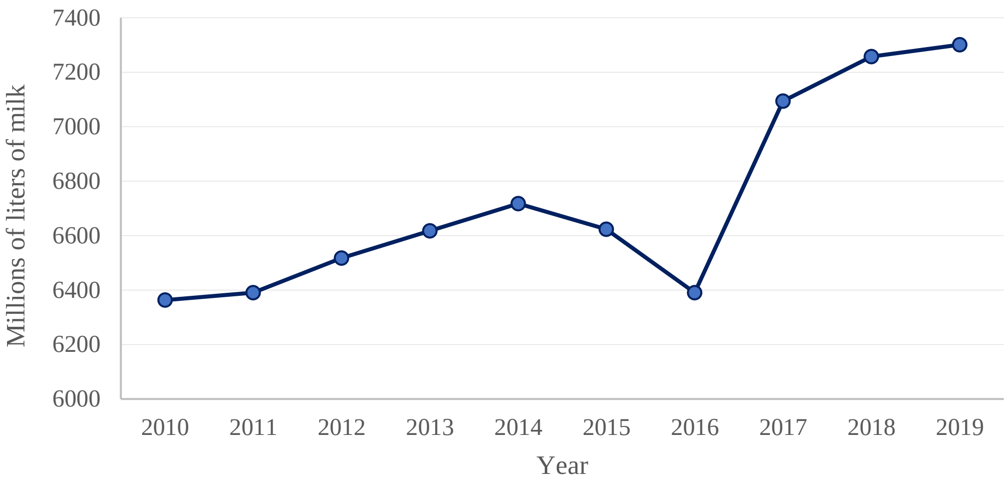


Figure 5.7. National production of milk from 2010 to 2019
Data source: FEDEGAN, 2020

Collection and transportation

Broadly speaking, the formal collection of milk involves two different agents, as illustrated above in Figure 5.3, namely, milk processing companies and intermediaries. Usually, intermediaries are a set of small or medium farmers who form a cooperative association to collect fresh milk, cool it, and then sell it to the processing industry. The association let producers access credit lines to afford a cooling system and get a collection center to avoid food loss and get higher incomes due to better milk quality. Hence, processing companies collect milk from medium or large producers directly at farms or in the collection centers using cooled tank trucks.

The stage is characterized by a high level of concentration in the collection of fresh milk. The five biggest companies concentrate about 55% of the formal collection of milk, and the first 25 consolidate about 80% of it. This situation results in a high asymmetry of the chain, where a large number of producers offer their products to a small number of processors who end up concentrating the bargaining power. This situation might be attractive for the entry of new processing competitors in the market, who would ensure sufficient supply for their operations. It represents, arguably, one of the dairy industry's significant problems nowadays, since most of this surplus of milk is sold to under regulation prices at informal markets. To point out, the collection of milk has grown around 18% over the last ten years, going from near to 2.6 billion liters collected in 2010 to almost 3.2 billion liters collected in 2019. Nevertheless, the gap between production and collection is about 4 billion liters of milk, as shown in Figure 5.8. It means the industry's current capacity can process approximately only 47% of the total raw milk production.

Regarding the location of the collection centers, out of the 32 administrative divisions in which the country is divided, collection occurs in 26 of them. Antioquia, Cundinamarca, Boyacá, Cesar, Nariño, Caquetá, Santander, Caldas, Magdalena, and Valle del Cauca accounts for more than 90% total volume of milk, which also corresponds to the central locations of processing plants of the large companies of the dairy industry.

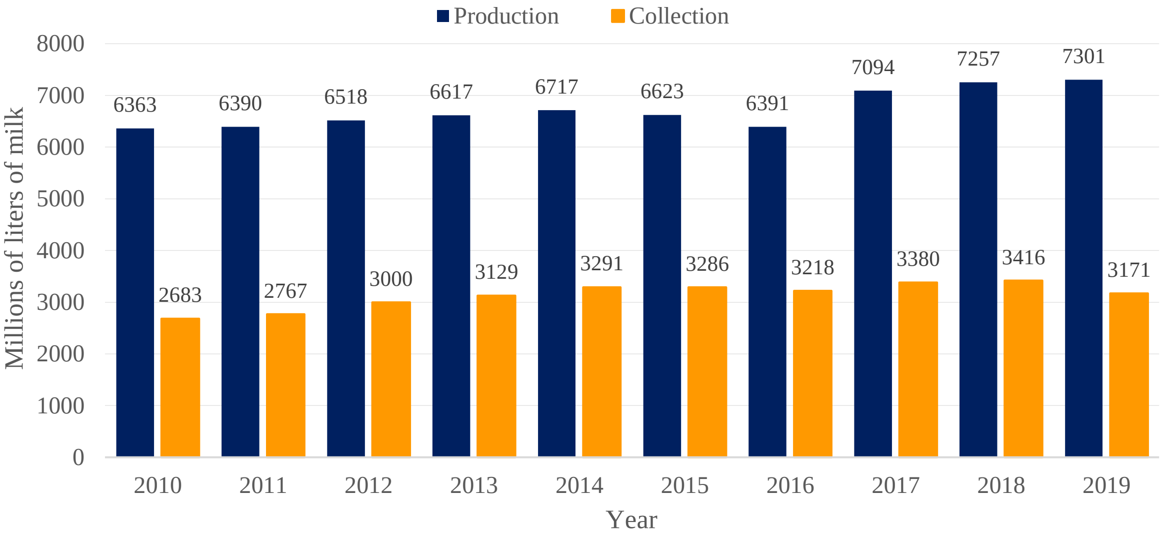


Figure 5.8. Production and formal collection of milk per year
Data source: FEDEGAN 2020, UPS 2020

Processing

The milk processing stage consists of pasteurizers, dryers, and dairy product processing companies. According to the National manufacturing survey (DANE, 2019), there are 155 companies in the line manufacture of dairy products. According to the new national regulation, those companies could be classified into micro, small, medium or large enterprises concerning their total incomes. About 6% of the companies belong to the category of large companies. These top ten companies account for almost 80% of the total market share as is shown in Figure 5.9. About 10% of the companies belong to the small and medium company category, and the remaining are micro-companies.

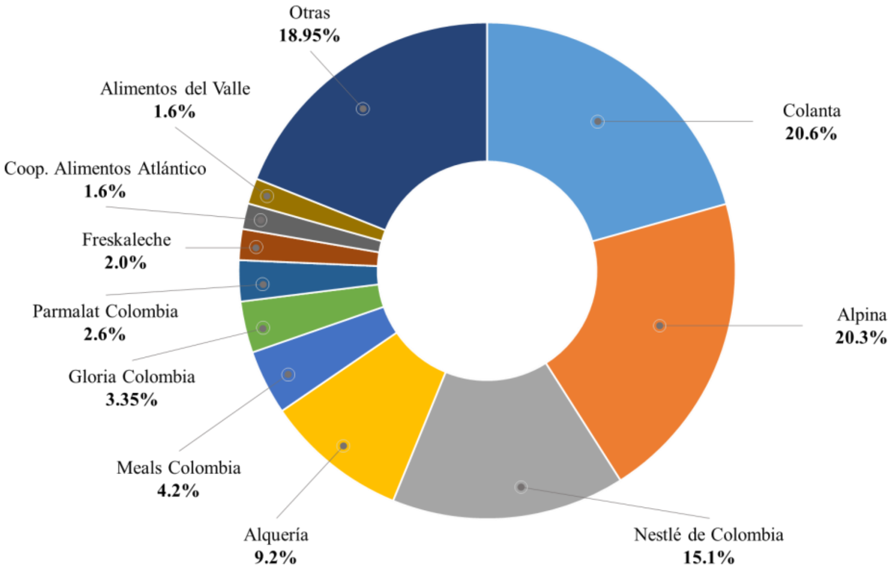


Figure 5.9. Market share distribution in the dairy industry
Source: (Asoleche, 2017)

Distribution and consumption

The distribution of dairy products to national or international markets occurs through different channels. First of all, the trade balance for dairy products in Colombia has been negative since 2009. The volume of dairy products exports from Colombia has been decreasing considerably over the last decade, representing, nowadays, less than 1% of the national production. In contrast, imports in the same category have considerably increased in the same period and are equivalent to about 4% of national production (MADR & UPRA, 2018). Therefore, most of the distribution occurs in the local market, here the traditional channel, meaning, neighborhood small food shops have the most significant participation, accounting for about 64% of the sales. Retailers represent about 26% of sales, hard discount 8%, and the remaining percentage of sales correspond to institutional purchases, army, hospitals, non-governmental organizations, etc.

According to the head of the office of planning and economic studies of the Colombian Cattle Ranchers Federation (FEDEGAN), Colombia's population has not a milk consumption culture. Although milk is a traditional product in the Colombian diet, the country's consumption per capita is around 158 liter per person per year. It is under the regular consumption of a milk producer country and below the minimum range recommended value by the World Health Organization (Bridge, 2015). For instance, it is below the consumption of other South American country producers like Argentina and Brazil. Hence, the promotion of dairy products' consumption is essential to bring the sector to a competitive position. Figure 5.10 displays the behavior on the apparent consumption of milk over the last ten years. The columns present the values for national production and total apparent milk consumption, while the line presents the average consumption per capita per year. Since 2016, MADR and other essential stakeholders in the sector have come developing campaigns to promote dairy products' consumption, aiming to raise the average consumption of milk to 170 liters per person per year. However, as MADR and UPRA (2018) pointed out, although consumption is growing, the share of national production is not, which exposes the chain's inefficiencies, mainly due to the price policy.

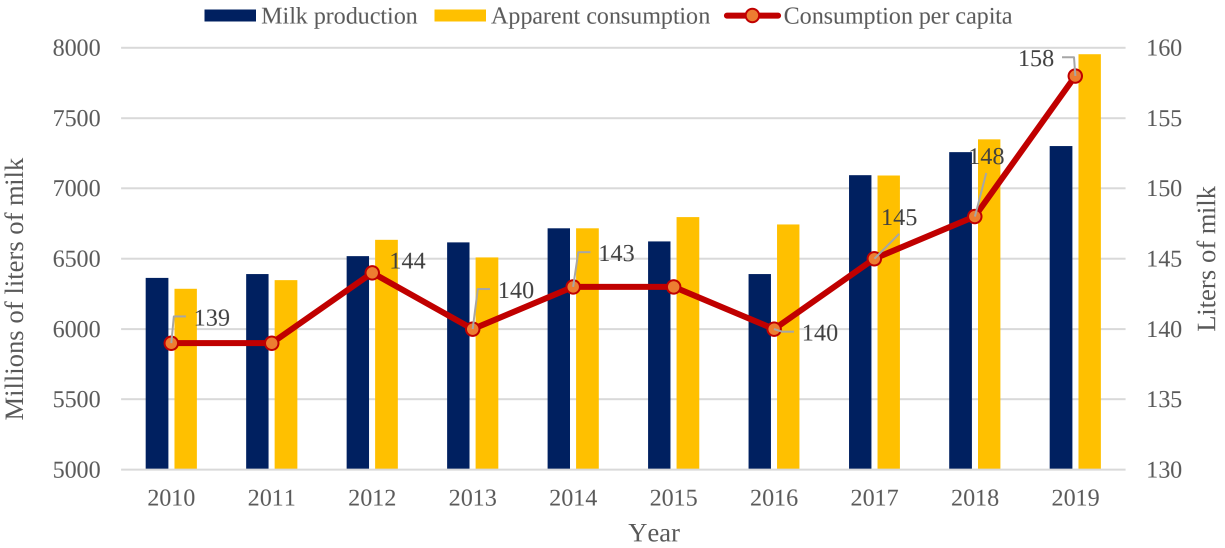


Figure 5.10. Total apparent consumption of milk and apparent consumption per capita
Data source: (FEDEGAN, 2020)

3. Environmental dimension

Several are the environmental impacts associate with farming livestock all around the world. For instance, it is a cause of land and water degradation, biodiversity loss, acid rain, coral reef degradation, and deforestation (Gerber et al., 2013). The production of ruminant meat and milk is associated with a relatively high greenhouse gas (GHG) production. Dairy cows and their manure produce GHG emissions, which contribute to climate change. Poor handling of manure and fertilizer can degrade local water resources. Unsustainable dairy farming and feed production can lead to the loss of ecologically key areas, such as prairies, wetlands, and forests. Grazing causes soil compaction and eutrophication due to excessive accumulation of manure and trampling. It increases erosion, loss of macronutrients, and degradation of grasslands (Rotz, 2018). Particularly, milk cattle accounts for around 20% of the total global emissions from livestock, being the second type of livestock contributing the most, just exceeded by beef cattle (Gerber et al., 2013). According to FAO, at the global level, the two main sources of GHG emissions in dairy supply chains are enteric fermentation, which represents about 43% of the total emissions, and pasture management, contributing to about 36% of it (FAO & GDP, 2018). Other sources include emissions from energy use in feed supply chains and emissions from energy consumption on farms that account for 10% and 8% percent, respectively.

Enteric fermentation is a natural part of the digestive process of domesticated and wild ruminants where anaerobic microbes, called methanogens, decompose and ferment food present in the digestive tract, such as celluloses, fiber, starches, and sugars, producing hydrogen (H_2), carbon dioxide (CO_2), and methane (CH_4). Enteric methane, as a by-product of this process, is expelled by the host animal through burping. At the same time, other by-products such as acetate, butyrate, among others, are absorbed by the animal and used as energy precursors to produce milk, meat, and wool (Knapp et al., 2014). Methane emissions are a function of the ruminant population, directly related to an animal diet, quantity, quality of feed, amount of energy consumed, animal size, production level, and environmental temperature.

Gerber et al. (2013) stated that CH4 emissions are higher in low productivity systems, going up to the fifth fold compared to more industrialized production systems. Higher milk yields imply a shift in the animal's metabolism in favor of milk production and reproduction instead of body maintenance, contributing to lower emission intensities. Although CH_4 has a shorter life span of a decade on average, while CO_2 may stay for hundreds or thousands of years, methane traps more heat than carbon dioxide, reflected in the global warming potential (GWP). Methane's comparative warming effect is 28 times greater than carbon dioxide per ton in a one-hundred-year period in accordance with the fifth assessment report of the Intergovernmental Panel on Climate Change (IPCC) (IPCC, 2013).

Pasture management is the second leading source of GHG emissions related to livestock farming. Here the expansion of pastures into forested areas is the principal cause of carbon release. Forests are essential carbon reservoirs since trees and other plants absorb carbon dioxide (CO_2) from the atmosphere as they grow, then this is converted into carbon and stored in its branches, leaves, trunks, roots, and in the soil. When forests are cleared or burnt, the stored carbon is released into the atmosphere, mainly as CO_2. In Latin America and the Caribbean, one-third of the emissions from beef production are related to pasture expansion into forested areas (Gerber et al., 2013).

In Colombia, livestock farming represents about 65% of the GHG emissions from the agricultural sector due to enteric fermentation and manure management. It contributes to nearly 40% of the forestry sector's emissions by converting natural forests to pastures (Tapasco et al., 2019). The livestock sector contributes to approximately 20% of national GHG emissions. Figure 5.11 presents the distribution of GHG emissions for the agricultural and forestry sector. Precisely, CH_4 is the most significant contributor in the sector, mainly by the ruminant digestion process. Indeed, livestock accounts for more than 50% of the total methane emissions at the national level. Nitrous oxide (NO_2), whose primary sources are manure management or fertilizer application in the second place. To mention, NO_2 has a GWP equal to 298 and remains in the atmosphere for 114 years, on average. On the other hand, as expected, forestry is dominated widely by CO_2 emissions due to natural forest clearance. Not surprisingly, as stated in the National greenhouse gas inventory, at the regional level, GHG emissions are directly related to cattle population, and 7 out of 8 detected cores with the highest deforestation rates in the country are related to livestock husbandry.

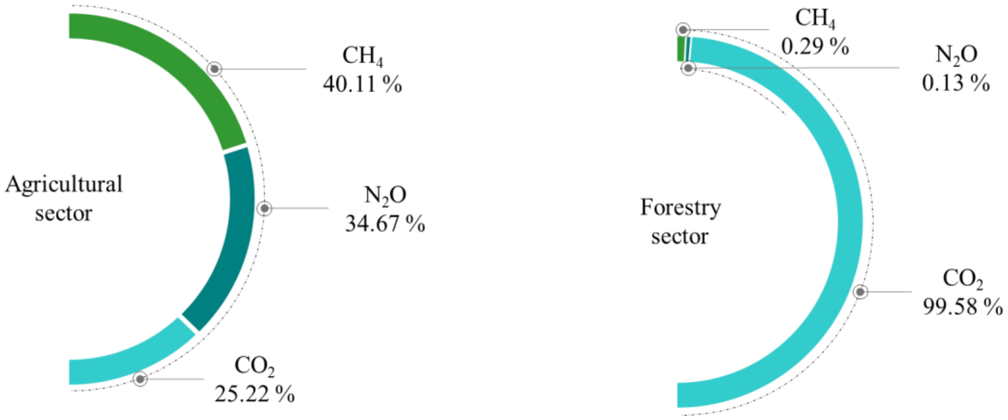


Figure 5.11. GHG inventory emissions of agricultural and forestry sector
Data source: (IDEAM, 2016)

Additionally, milk production also puts tremendous pressure on hydric resources, making necessary its management and location. Water is used for animal consumption, milk cooling, cow cooling, cleaning, and sanitizing equipment, irrigating crops, moving manure, among other farm activities. A high-quality water supply is essential to dairy farms. Particularly in Colombia, pastures account for near 25% of water's total demand in the agriculture sector. Moreover, dairy farm expansion also affects some water regulators ecosystems, for example, 3.6% of pastures in dairy farms are located in wetlands, and 1.9 % are located in moors. The situation often leads to drying water sources, eutrophication due to inefficient or inexistent manure management, and water pollution.

One of the most common livestock activity stereotypes is the excessive use of land, often contrary to the soil's natural vocation. The expansion of the dairy sector threatens croplands and food safety. Increasing local and international consumers' commitment to sustainable and safety practices in agriculture demands the industry to turn into more sustainable practices. Chará et al. (2017) stated that cattle ranching has traditionally relied on extensive systems with low stocking rates in Colombia and other Latin American countries. As mentioned before, more than 70% of the available land for agricultural activities in Colombia is used to develop some cattle husbandry, including beef and dairy cattle (Leiva Barón et al., 2016). The conflict on land use is evident in the Colombian livestock sector, as is presented in Table 5.2.

Table 5.2. Use of land in Colombia
Data source: FEDEGAN 2020, IGAC 2012

	Current use (ha)	Potential use (ha)
Agriculture	4'617.116	21'500.000
Livestock	39'017.179	20'000.000
Forest plantation	569.996	4'000.000
Other uses	1'292.128	

Currently, the total area used to develop livestock activities exceeds by more than 10 million hectares the potential area to withstand this activity. According to MADR, about 34% of the area occupied for milk production in Colombia is out of the agricultural frontier. It means they are located in areas with environmental constraints. Hence, it demands a reallocation of the dairy farms and a definition of growth boundaries to the sector aiming to ensure food security and make the most of the soil conditions and potential. To this end, UPRA has been working on the classification for the potential use of land. For instance, according to soil components, soil characteristics, rainfall, access road, access to markets, access to feed suppliers, labor cost, and other environmental and socioeconomic variables, Colombia has about 24 million hectares to develop dairy production activities. In detail, Colombia has 4.4 million hectares with high potential for developing the activity, about 6.5 million with medium potential, and 14 million in the low potential category.

Additional environmental impacts are caused downstream of the supply chain. Direct and indirect emissions for processing milk, wastewater disposal, and fuel combustion for transportation activities. According to (Notarnicola et al., 2017), who evaluate the environmental impacts for a basket of representative food products in Europe, the agricultural link makes the most significant contribution due to agronomic and zootechnical activities. It is followed by food processing and logistic activities due to energy intensity and related emissions occurring during the heat, steam, and electricity production during industrial processing and fuel combustion during transportation. These results agree with previous studies mentioning (Eberle & Fels, 2016) and (Muñoz et al., 2010). These studies also pointed out the relevance of animal products, especially meat and dairy products, including cheese, butter, milk, yogurt, to GHG contribution. In particular, (Notarnicola et al., 2017) highlight the impact of agriculture on relevant environmental impact categories such as climate change, acidification, human toxicity, cancer effect, eutrophication, and land use.

4. Social dimension

The livestock sector is one of the most significant contributors to poverty reduction. It constitutes livelihood for vulnerable communities all around the world. More than 500 million farmers rely on livestock herding for livelihood. Arguably, to a vast number of smallholders in precarious economic conditions, farm animals are a significant asset, representing capital, incomes, and a source of high-quality nutrients for their families. Considering the trend in demand for livestock products, the livestock sector can contribute to poverty reduction and hunger eradication by promoting sustainable growth, inclusive social development, and efficient use of natural resources (FAO et al., 2018). According to FEDEGAN (2018), Cattle raising is the most extensive economic activity in the Colombian countryside. It takes place in all regions, all topographical elevations, different scale productions, and different productive orientations. Livestock accounts for about 6% of the employees at the national level and about 20% of employment in the agricultural sector.

As mentioned before, a large percentage of the cattle farms in Colombia, near 44%, could be classified as subsistence farming. To describe it, it usually consists of informal business, where production control or records are rarely kept. Animals usually are inherited, and the genetic development of the breeds to milk production is scarce. The labor is most familiar, and the production is used for farm and family consumption, while the rest might be sold to local artisanal producers at low prices (Bridge, 2015). About 45% of the farms belong to the category of emerging farms. Farmers in this category have an entrepreneurial vision at managing their farms. Willing to meet regulations and obtain cattle health certifications if it represents profits in the future. Animals are provided with better feed quality than subsistence farming, and there is a transition to specialized breeds (FEDEGAN, 2018). Milk production is usually sold in the formal market to medium-sized companies or large local ones, directly or through cooperatives, as explained in Subsection 5.2.2. Farms are usually managed for an employee, who can settle on the farm with family, have a contract, and receive legal benefits. Other employees might be contracted for specific tasks per day or week as required. Finally, the remaining 10% of the farms could be considered profitable businesses. Farms with more than 50 animals, professional management of breeds, obtaining high volumes, and high quality. Companies managed under law regulations keeping production and accounts records, certified in good farming practices. Managers and technicians with a professional degree in zootechnical sciences, veterinary, agronomy, or business administration are in charge of developing a business plan, ensuring resources for animals' wellbeing, and ensuring productivity and quality standards compliance. Generally, milk is sold directly to large processing companies, solely, with whom a very close relationship is established.

According to (MADR & UPRA, 2018), with data from the National Department of Statistics (DANE), 63% of farm holders consider themselves as poor population. However, only 35.6% of rural households have incidence in the multidimensional poverty index (MPI). MPI complements traditional monetary poverty measures by capturing the acute deprivations in health and wellbeing, quality education, and living standards that an individual face, simultaneously. It includes nutrition, years of schooling, school attendance, drinking water availability, electricity, housing materials, among others (Alkire et al., 2020). Considering Colombian rural households, some living standard conditions and quality education stand out. Low educational achievement is a factor affecting 85% of rural households. For instance, about 59% of producers have only reached the primary school level, 16% have not reached any formal education degree and only about 4% of producers are professional or technicians. Moreover, it is mentioned that 95% of the rural households do not have access to sewerage and 65% of them lack water services.

Regarding gender distribution, it is reported an even distribution in rural households, with 53% men and 47% women. Of the total, about 42% are between 27 to 59 years old, 25% are 18 to 26 years old, and 15% older than 60. Distribution in the labor market is not that even. According to (DANE, 2019), 76% of men develop some sort of labor, 6% home tasks, around 7% study, and 3% search for a job. While only 20% of women are reported as an employee, 69% are involved in in-home tasks, 7% study, and 1% searching for a job. However, the sector's informality labor rate goes up to 86%, which means that only 14% of the employees have a legally established contract receiving all the benefits, waves, and compensations assured by a regular permanent contract.

Regarding employment quality, the sector is characterized by generating more family employment than external employment, with a high non-monetary remuneration component. As shown in Figure 5.12, this type of employability is a distinctive feature of smallholder production, which are the vast majority, as mentioned before (see Figure 5.5). The greater the herd, the higher the demand for external labor. Similarly, as the number of animals per productive unit increases, so does the permanent labor. Nevertheless, occasional hiring or *jornal* retains high participation as a form of hiring regardless of herd's size.

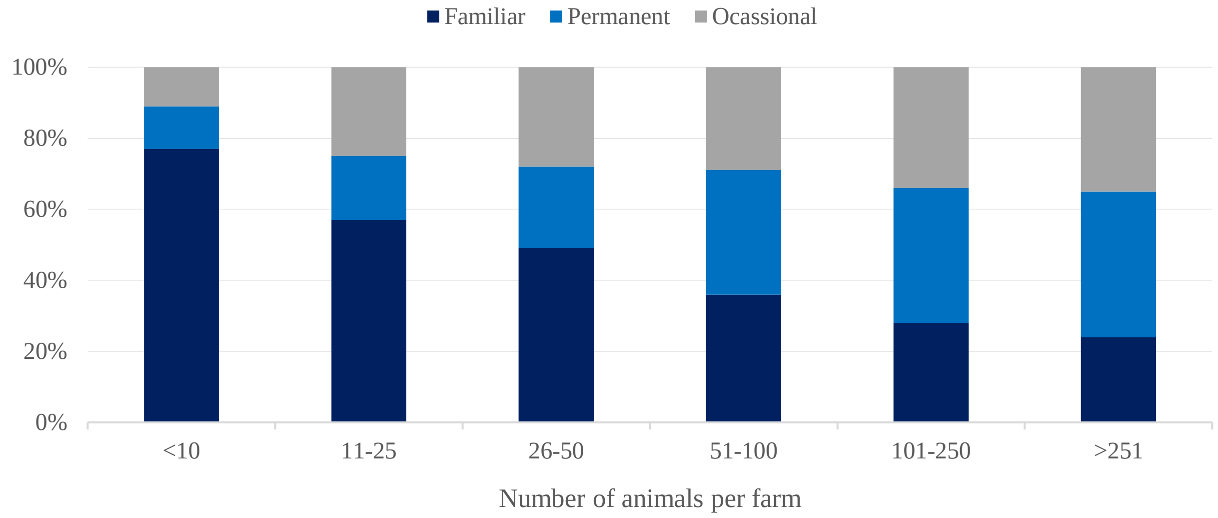


Figure 5.12. Labor type participation per farm size.
Source: (FEDEGAN, 2006)

Nevertheless, national milk production, including dairy specialized farms and dual-purpose farms, generates about 700,000 permanent employees. According to Fedegan, specialized dairy farms and dual purposes also differ in the capacity of generating jobs. It is estimated that between 7 and 8 employees are required by every hundred animals in specialized dairy farms, while 5 to 6 for the same number of animals in dual-purposes farms (FEDEGAN, 2006). The most significant milk shed in the country, Antioquia and Cundinamarca, has the highest labor costs, partially because of qualified workers' demand for milking activities. In other regions, livestock activities compete for workforce with other, usually, more attractive industries, such as oil industry, which increases the average daily wage.

Other distinguishable social impacts in the industry are presented in the consumption stage. The high consumption of non-pasteurized milk represents a risk to consumers' health due to the high propensity of milk as a medium for bacterial growth. In this regard, there is a remarkable difference in the consumption of dairy products considering socioeconomic levels. As mentioned before, the country's average consumption of industrialized milk in 2019 was 158 liters per capita; however, in a more in-depth view of the consumption, notorious differences stand out. For instance, consumption in the lowest socioeconomic level is about 39 liters/person/year, while in the highest, it is 193 liters/person/year, as is presented in Figure 5.13. Socioeconomic stratification is parametrized mainly by housing conditions and living environment. It expresses a demonstrable socioeconomic way of life. In this sense it is directly related with the capacity acquisition of families. Therefore, the data displayed in Figure 5.13 is partially explained by the high cost of dairy products in the market, market penetration, and the notorious difference between economic conditions in rural and urban areas.

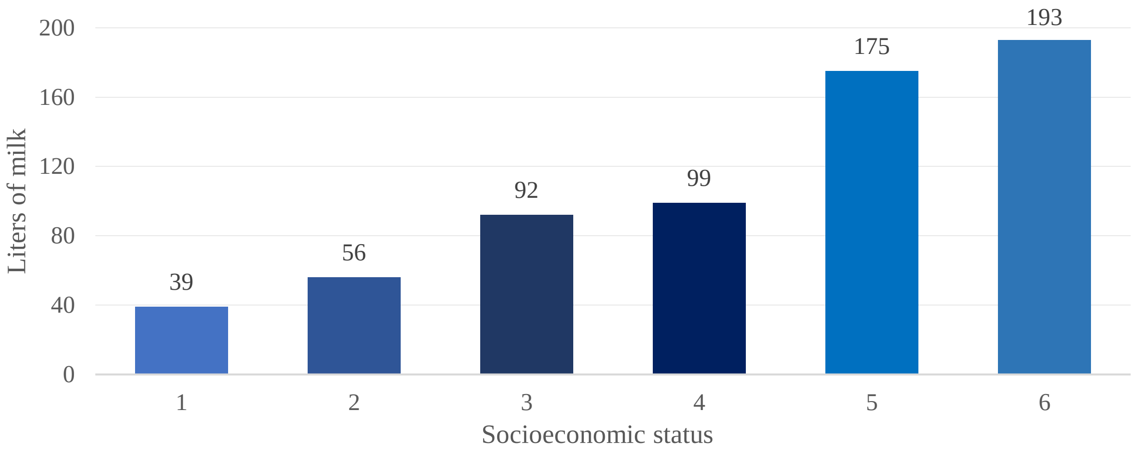


Figure 5.13. Average milk consumption per capita by socioeconomic status
Data source: FEDEGAN, 2018

5. Challenges for sustainable development in the dairy industry

In a broad sense, producers, transporters, industrializers, and consumers will be sustainable when they are economically viable, ecologically safe, socially fair, culturally appropriate with a unified and holistic vision of the productive chain. From the supply chain's characterization in the previous sections, it is possible to enumerate some current dairy industry challenges to reach sustainability. However, since the aim of the work is to evaluate the application of public policies and their long-term impacts in the redesign of supply chains, it is necessary to give the dairy supply chain a context, considering external stakeholders. Specifically, this subsection is intended to establish a shared sustainability concept in the sector, diluting what sustainability means for stakeholders and how they display a sustainable dairy industry.

The dairy industry has been identified as an excellent ally of the country in reducing poverty, violence, closing the gaps between urban and rural livelihoods, and offering high nutritional value products. Moreover, as detailed in section 5.3, it plays a fundamental role in the country's intentions to reduce GHG emissions, stop deforestation, and give appropriate land use. Not surprisingly, during the last years, national institutions have come working in a supporting framework to the sustainable development of the livestock sector and particularly the dairy industry (Tapasco et al., 2019). The framework includes, among others, the document CONPES 3675 National policy to improve the competitiveness of the Colombian dairy sector (DNP, 2010b), Dairy sector business plan (MCIT & PTP, 2016), Agricultural sector plan for the mitigation of GHG (MADR, 2017), National Appropriate Mitigation Action for the sustainable bovine livestock sector, Colombian livestock Roadmap 2018 - 2022 (FEDEGAN, 2018), which are covered by national development plans including, National Climate change policy (MADS, 2014), Nationally Determined Contributions (Colombia, 2018) and the Program of productive sectorial transformation (DNP, 2010a).

These documents agree on highlighting the relevance of milk producers and processors in the supply chain's sustainable development. To the dairy industry's strategic business plan, the sector might be understood as a pyramid of value-focused on competitiveness and sustainability. The emphasis is placed on the joint and coordinated work of producers and industry to fulfill the development objectives of the sector. Simultaneously, other agents such as suppliers, distribution agents, agencies, and other institutions provide technical and legal support to meet domestic and foreign consumers' needs and consumer trends, as shown in Figure 5.14. Within this framework, most of the strategic development plan's burden falls on shoulders of producers and processors that constitute, in the supply chain, the core and the engine of the strategic plan to reach sustainable conditions (MCIT & PTP, 2016).

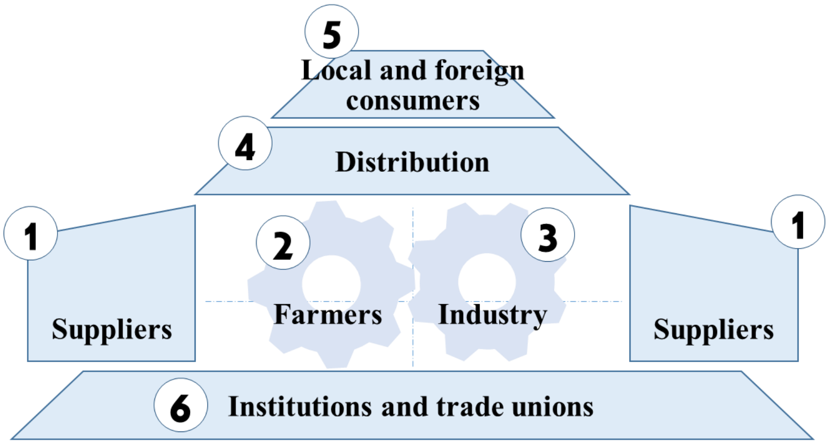


Figure 5.14. Value pyramid of the dairy sector
Source: (MCIT & PTP, 2016)

Review of previously mentioned documents presenting the current challenges and the sector's future vision serve as input for identifying the most relevant factors to reach sustainability in the sector at the economic, social, and environmental dimension. Some of the major problems affecting the processing stage include lack of innovation, scarcity of strategy activities for accessing new markets, and minimal emphasis on international markets. Moreover, it is mentioned that, for some regions, processing facilities are located away from production areas, which causes transportation problems on collecting milk. Being milk a perishable good, these difficulties cause cost overrun, impacting the incomes of farmers expenditures of processors. Table 5.3 presents a list of the leading sustainability challenges in the supply chain.

Table 5.3. Current challenges in the dairy sector by sustainability dimension
Source: Author’s synthesis

Sustainability dimensions		
Economy	**Environment**	**Society**
Scattered low production scale	Deforestation	Low-level education
High inputs cost	Use of land conflicts	Low IT access
Poor road infrastructure	Enteric fermentation GHG emissions	Low milk consumption
Lack of innovation	Water use conflicts	Low incomes
Business informality	Biodiversity loss	Rural violence
Insufficient production capacity	Lack of pastures management	Low-skilled rural labor
Growth of imports		Difficult access to project funding
High fuel and energy costs		Low associativity
Lack of clusterization		No entrepreneurial mindset

Since the analysis unit goes beyond a focal company, public policies encompass the direction of development of the sector to the whole industry. Aside from the individual effort of producers or processors at seeking their own competitiveness and profitability to contribute to the global competitiveness of the dairy sector at the national level, the productive transformation of the sector is undoubtedly a public policy objective aiming to:

- Promote milk consumption, and encourage milk processors to increment the milk collected, incrementing farmers' participation in the formal sector and benefiting the consumer by offering healthy tested products.
- Increase farm productivity by having a more efficient use of natural resources, animal and livestock farming improvements to reach international competitive values of milk production per cow and hectare.
- Ensure economic growth and fair incomes for milk producers to reduce poverty and enhance rural areas' living conditions.
- Consider the potential use of soil as a base factor to the production's location and organization by removing livestock husbandry activities from areas under protection, natural parks, moors, and other restricted ecosystems and releasing overexploited land to more accurate land uses.

Sustainability in the dairy chain is understood as the need to respond to growing demand, in quantity and quality of milk, without compromising the quantity and quality of natural resources required in the whole process. It implies that resources are used at a rate that does not exceed the intensity at which these resources are being produced or assimilated by the system. At the same time, it deals with encouraging processors to increase industrial capacity and gain share at international markets, bringing benefits for themselves and also for farmers at the primary stage of the chain.

With this issue in mind, we decided, within our case study, not to focus at the scale of a single company, but to consider the entire production industry of Colombia within the scope of our study. Thus, in order to put in evidence, the differences between the various region of Colombia, we considered the scale of the region as a relevant subdivision for our model.

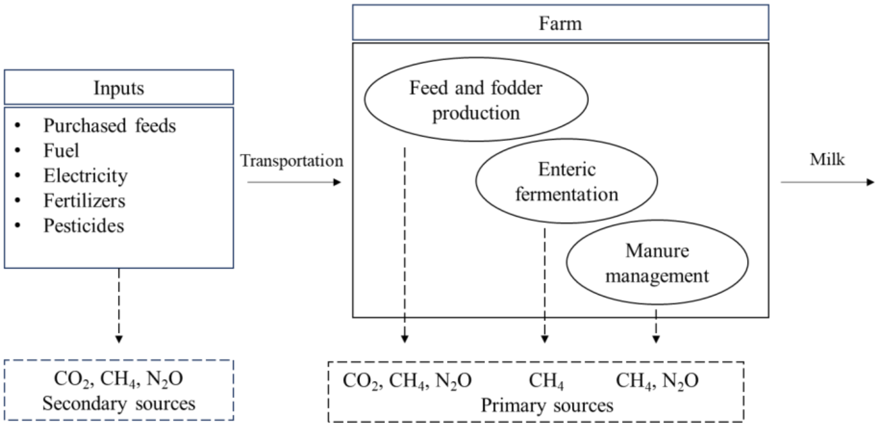
6. Sustainable objectives

The measurement and evaluation of sustainability require the definition of measurable objectives and accurate indicators. This section presents the indicators used to evaluate sustainability at the supply chain level, considering the dairy industry's main challenges in Colombia. To the best of our knowledge, there are no previous works defining sustainability criteria at the farm level in Colombia to be included in the modeling to design a supply chain network. At least two conditions are desirable to those criteria. First, to be linked with a measurable long-term objective in the industry, and second, to be represented by a quantitative expression.

The use of individual indicators allows taking a holistic view of sustainable development in each pillar, avoiding weighting sums of indicators that sometimes incur compensation between indicators. The major criticism of composite indicators is that the use of weights might disguise one indicator's poor performance with another indicator's good performance, causing misleading interpretations and leading to wrong decisions (Goswami et al., 2017). Moreover, since the long-term supply chain network design, considering policies development, involve the comparison of each indicator value with a reference value determined by either a global commitment trade, a national policy, or a sectorial objective, the use of individual indicators is useful to compare the current state of the indicator with the desired value.

The economic dimension is represented by one indicator. The total cost includes procurement costs, processing costs, investment costs for adding, removing, or replacing capacity, and the cost incurred by transporting materials from farms to retailers through every stage of the supply chain. This indicator is associated with goal 8 and specifically with target 8.1 that claims to sustain per capita growth under national circumstances. Run cost-efficient businesses is the essential compromises of firms to achieve sustainability.

(*a*) Milk production



(*b*) Dairy processing

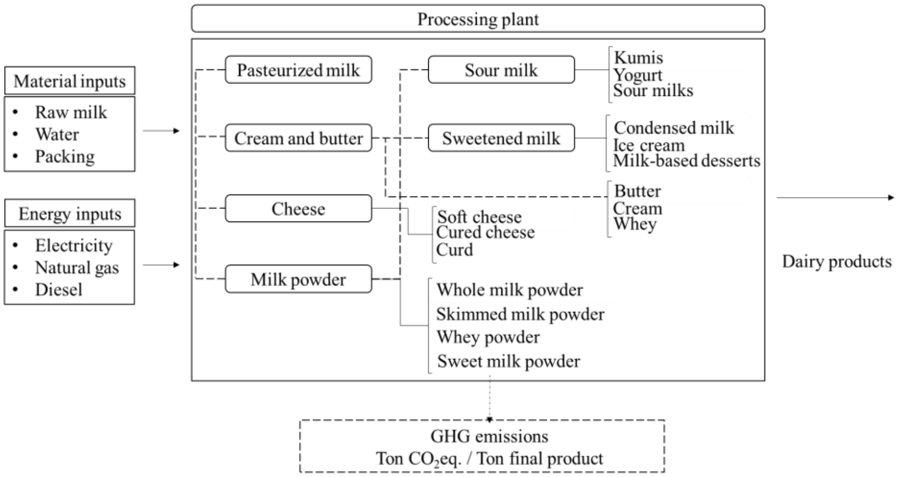


Figure 5.15. Simplified Input-Process-Output milk production and dairy processing processes
Source: (*a*) (Garg et al., 2018), (*b*) (Nutter et al., 2013)

Regarding the environmental dimension, two indicators will be evaluated in our model. First, GHG emissions calculation covers production, processing, storage, and transportation linked to the amount of milk produced, transformed, and transported among facilities and till the retailer. Hereof, the indicator is associated with the target 12.a and 13 seeking to establish actions to combat climate change. As proposed by the IPCC methodology (IPCC, 2006) , we compute the total GHG emissions from one activity as the product of an emission factor associated with the activity and the activity level. For instance, the associated emissions at producing one liter of milk at one farm in one region considering the differences in production systems, specialized dairy system, or dual-purposes system. To this aim, we consider the farm system and the dairy industry as input-process-output boxes as presented in Figure 5.15(*a*) and (*b*), respectively. While the transportation among facilities is a product of the number of journeys, considering full truckload, multiplied by the emission factor, which includes distance between facilities and energy intensity according to the vehicle type.

Additionally, being the transformation of forest land one of the major cause of deforestation. We consider an indicator to calculate the number of hectares in each region dedicated to milk production. The factor considers differences in the animal stock rate to the different production systems and regions. This indicator is directly aligned with the sustainable development goal number 15, aiming to protect, restore, and promote sustainable use of territorial ecosystems, reverse land degradation, and detain biodiversity loss.

Finally, the social dimension considers two objectives. In response to target 9.3, which aims to increase the integration of small-scale businesses into value chains and markets, the increasing participation of farmers in formal and regulated economic activities is considered through the percentage of milk collected by formal companies. Several factors, such as demand, difficult road access, and profitability, lead farmers to sell their production to non-formal constituted firms, which pay lower prices. These ad-lib bargains affect the farmers' economic performance and the whole industry, letting into the market products with no compliance with health standards and unbeatable prices. Finally, in line with SDG number 8, job creation because of production and processing distribution capacity rise by region is accounted as an indicator of the social impact of the redesign of the supply chain in the long-term. As a synthesis of what have been said regarding the understanding of sustainability in the dairy industry in Colombia, Table 5.4 presents the sustainability key indicators selected for the case study and the associated sustainable development goals (SDGs), related to them.

Table 5.4. Sustainability indicators and SDG's considered in the ex-ante sustainability assessment

Sustainability Dimension	**Impact category**	**SDG's**	**Indicator**
Economic	Total operational cost	8	Total annual processing and distribution cost
Environmental	GHG emissions	12, 13	Tonnes of CO_2 eq. produced by production, processing, and transportation emissions
	Use of Land	15	Number of hectares of land used for dairy cattle activities
Social	Formal businesses	9	Percentage of milk production collected in the formal channel
	Employment	8	Number of jobs in production and processing activities

7. External scenario drivers

To define scenario characteristics in the dairy industry's development, a set of external drivers is analyzed. These parameters cover changes in the market as well as the adoption of more efficient livestock husbandry techniques. Following some essential assumptions are highlighted.

Increasing milk consumption: An essential element for the straightening of the dairy sector in Colombia is the dairy products' local consumption. As FAO stated and used in previous studies, milk consumption in the country is estimated considering the dynamic of population growth (OECD & FAO, 2020; Schmit & Kaiser, 2006). The promotion of consumption of milk aims to raise the average annual consumption per capita in 30 liters. By 2016 the average consumption per capita in Colombia was 140 liters of milk, which correspond to a medium level consumption according to the Pan American Dairy Federation (FEPALE) (MADR & UPRA, 2018). Promoting consumption campaigns in the country has reached a continuous increment from 145 in 2017 to 148 in 2018 and 158 liter/inhabitant in 2019. The goal is to reach at least 170 liters per capita per year by 2022.
In a trending scenario to estimate the demand for 20 years ahead, we consider a 2% per capita consumption rate increasing per year until it reaches 170 liters. A conservative yearly behavior between minus 1% to positive 1.5% will be considered from that point on. The annual growth is a conservative estimation based on previous years' growth rate.

Increasing productivity rate: The dairy sector is in continuous development because of different changes that involve advances in research, transfer, and appropriation of technologies in pastures and forages, genetic improvement, increases in livestock inventory among others. These variables are not directly considered in the mathematical model. However, they might affect total production and productivity per animal and per land area in the long-term. In this regard, a trending advancement of the sector is considered, based on the last decade's behavior. Based on the milk production register from 2010 to 2019, a milk production increment of about1.5% per year is included in the sector's behavior.

Silvopastoral system implementation: Global demand for milk is expected to grow over the next decades, requiring a significant amount of natural resources to satisfy it. In countries like Colombia, where livestock husbandry takes place in vast pasture fields, pressing overproduction threatens biodiversity by changing land use. Nevertheless, recent studies have demonstrated the possibility of silvopastoral systems implementation. This system introduces environmental-friendly cattle production, improves productivity per animal, enhances biodiversity, and works as a sequestration system for GHG emissions (J Chará et al., 2019).

Recent studies on NAMA's (National appropriate mitigation action) for the agricultural sector in Colombia have highlighted silvopastoral system implementation as one of the most critical agricultural sectors' activities to mitigate climate change. In accordance with (MinAmbiente, 2014) this mitigation action has the most significant reduction potential of $MtCO_2eq$. in the agricultural sector. Additionally, it presents a negative cost in the marginal abatement cost curve, as presented in Figure 5.16. Specifically, the agricultural sector accounts for a potential reduction of 344 million tons of CO_2 eq. from 2010 to 2040. Out of the total, 337 million are related to the livestock sector, and 208 million correspond to the silvopastoral system's action, showing the measure's relevance to meet the intended reductions of the sector and the country (Behrentz et al., 2014).

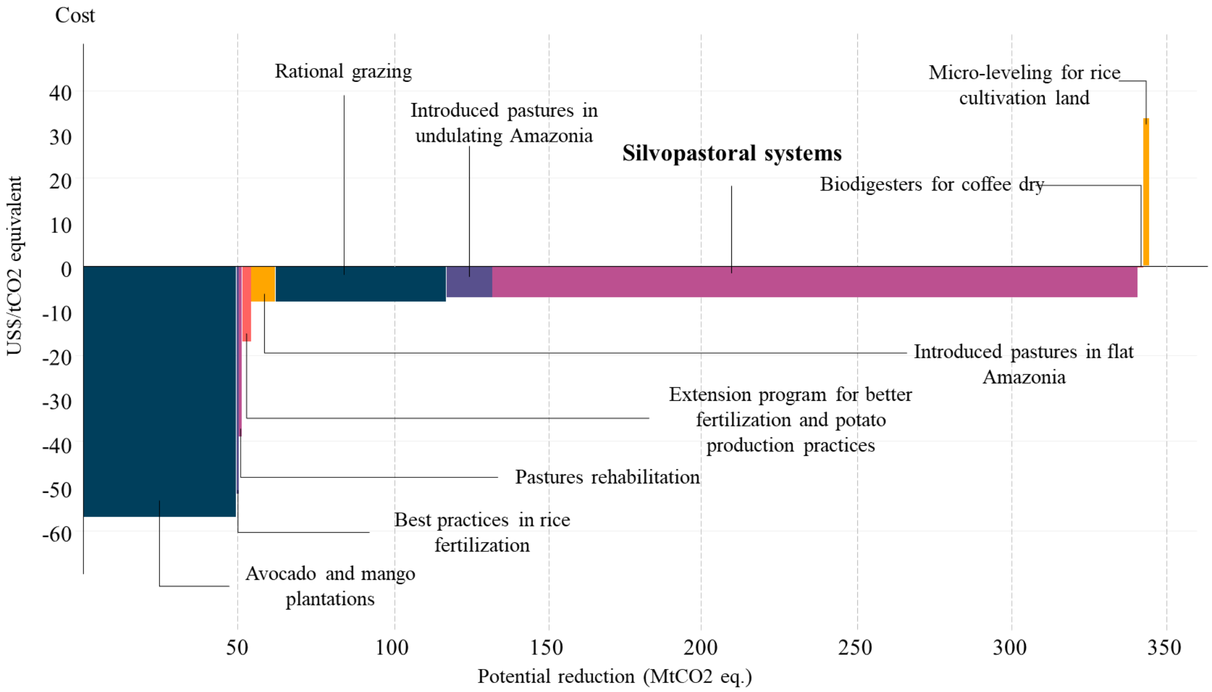


Figure 5.16. Marginal abatement cost curve of the agricultural sector
Source: (Behrentz et al., 2014)

Marginal abatement cost (MAC) curves present the relationship between the cost-effectiveness of different mitigation options and the total amount of CO_2 eq. reduced. Mainly, it reflects the additional cost of reducing the last unit of carbon. MAC curves focus on the direct cost associated with investment cost, operation cost, and maintenance cost for abatement measures (Kesicki & Strachan, 2011). Figure 5.16 shows the cost and the mitigation potential of each measure in the agricultural sector in Colombia. Each bar represents a mitigation option. The bar's width shows the potential of GHG emissions reduction expressed in $MtCO_2$ eq., while the height of the bar indicates the cost of reducing one tCO_2 eq. by applying the measure. The total cost of the measure could be calculated by calculating the area of the bar. The total width of the graph represents the total mitigation potential of the sector, and the sum of the area of all the bars sum up the total cost of all mitigation measures. The cost of each action represents the cash flow over the useful life of the project. Investment costs, operating and maintenance expenses, salvage costs and revenue generated by the action are considered. Thus, a negative cost represents savings compared to the baseline scenario in which no action is taken (Behrentz et al., 2014). A more detailed explanation of MAC curves, their construction and classification and its usefulness to visualize reduction opportunities for climate change in the agricultural sector can be consulted in (Kesicki & Strachan, 2011) and (Eory et al., 2018), respectively.

Electrical fleet for distribution: Several industrial partners are concerned about the impact of transportation on environmental performance. Some of them have gone forward with regulations to make higher and more challenging compromises with green production. For instance, some of the most relevant processing industries have signed compromises to work to be neutral carbon within a decade. These actions demand work in from different perspectives, processing, packing, and distribution. Indeed, distribution through all the supply chain contributes to a high number of emissions since the routes to collect and distribute milk work every day. Some efforts have been made to minimize distribution's environmental impact, such as minimizing the routes' driven distance through optimization models. Recently, some companies have been working with what seems a promising alternative to going further on reducing GHG emissions from the collection and distribution process using electric vehicles. To promote the use of this type of vehicle, some national policies have been set. Reduction in taxes, import fees, and elimination of mobility restrictions are some of the advantages to stimulate the adoption of this technology.

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Chapter 6 Time to Sustainability

The content of this chapter is part of the paper submitted for publication as: Moreno-Camacho, C. A., Montoya-Torres, J. R., Jaegler, A., Gondran, N. "Agrifood Supply Chain Network Design Under Sustainable Development Policies". *European Journal of Operational Research*

Considering a wide-industry approach and the changes caused because of action and policies aiming to meet climate change and sustainable development objectives, this chapter presents a mathematical model to the design or re-design of supply chain networks under policies implementation. The chapter revisits a model presented previously in (Kannegiesser et al., 2015) and go further by considering uncertainty in the expected results of policies and the construction of reference scenarios in line with the IPCC guidelines (IPCC, 2006). The model is intended to work as an ex-post assessment tool for the implementation of policies at sectorial level. It estimates the effects of action and policies in the three dimensions of sustainability, while considering the strategical decisions associated with the location, capacity, and distribution in supply chain networks.

1. Introduction to sustainability assessment in policies actions

Evaluation of sustainability at the corporate level has received increasing attention since the spreading out of the triple bottom line concept. From that point on, the evaluation of commitment with sustainability has been extended to every supply chain member due to the interactions of a company with both, down or upstream companies in the supply chain that end up by affecting the social, the environmental and finally the economic performance of the company. However, there is a constant inquiry to step out of the company approach to consider a wide industry focus, although, the latter is not easy since the access to information upstream further than supplier in Tier 1, results one of the big barriers (Muñoz-Torres et al., 2018; Schöggl et al., 2016). However, considering policies in the development of the sector might avoid this difficulty since, at this macro-level, it is plausible to consider that the development of the industry is influenced by overall macroeconomic factors, such as demand, labor costs, land costs and availability, rather than individual competitive behavior of single companies (Kannegiesser & Günther, 2014).

Classical approaches evaluating sustainability assessment at supply chain level, focus on a single company, which ends up shifting the burden to lower levels of the chain, but without considering the actions or plans to be developed. Moreover, there is a constant lack of definition of sustainability objectives. Although generic models offer the possibility of deciding between a set of equally optimal solutions in the presence of conflicting objectives, the applications fail to provide acceptable or desirable limits for the objectives under evaluation. The concept of development is closely linked to the achievement of objectives and it is no different when talking about sustainable development. According to (Sala, Ciuffo, & Nijkamp (2015) when talking about sustainability assessment tools, the definition of objectives becomes indispensable, otherwise the measurement does not fulfill its role within the development dynamics. For example, a decrease in the emissions intensity of a company through the redesign of its operations does not in itself imply a sustainable practice without the existence of an objective to evaluate or contrast it.

In this regard, along with the growing concerns about climate change, poverty, hunger, among other social and environmental issues, there has been a commitment to the definition of global objectives and agreements at the international level. For example, the definition of the Millennium Development Goals (SDGs) is accompanied by targets in every category to be met by the end of the next decade (United Nations, 2020). Another example is the commitments per country to the reduction of emissions that aim to avoid a two degree increase in global temperature in relation to the pre-industrial era. One of the ways of establishing objectives for the evaluation of supply chains involves the application and evaluation of public policies for the development of these types of production chains. Policies may be sectoral, regional, or national and may include the promotion of various activities to achieve the objectives. Types of policies and actions include regulations and standards; taxes and charges; subsidies and incentives; information instruments; voluntary agreements; and implementation of new technologies, processes, or practices (IWR, 2016).

In sectors constituting focal points for the regional or national development, the evaluation of policies at the sectoral level is decisive for the evaluation of the country's development. In this sense, policies allow the coordinated development of the sector under the parameters that best suit the common development by promoting clusters and enhancing productive capacities according to regional strengths. Moreover, in addition of including economic, environmental, and social dimensions, the political dimension is also included as a factor in the sustainable development of companies when considering policies and actions.

2. Classification of the sustainability assessment tool

Since the mention of the sustainable development concept in the Brundtland report (WCED, 1987), the proposition of trustable and useful methods, methodologies, and tools has become one of the major challenges faced by researchers and practitioners, to assess the performance of systems and companies in the three different pillars of sustainability, namely economy, environment and society. Research on sustainability assessment tools (SAT’s) have evolved during the last two decades and still attract the attention of researchers nowadays. Several considerations are involved in the construction of accurate SAT’s. For instance, SAT´s might be classified according to different categories, including, timing and valuation perspective (Gasparatos & Scolobig, 2012), level of analysis, target group and data aggregation (Bélanger et al., 2015), and according to the methodological approach to evaluate the defined sustainability indicators (Lebacq et al., 2013) as presented in Figure 6.1. Considering the wide range of alternatives for the construction of SAT, it is pertinent to detail the characteristics of the one proposed here to the evaluation of sustainability at the design of supply chain networks. It is important to highlight how the characteristics of the measurement tool match the problem’s features and decision.

According to the time of evaluation, SAT’s might be categorized in ex-ante or ex-post assessment tools. The former is a forward-looking activity, which considers the expected effects on the implementation of policies, actions, or projects, aiming to compare it with the trending case in which no changes are done (Business as usual). It is usually based on forecasts of emissions drivers such as population growth, economic activity, trends development supported by historic data and the estimated impacts introduced by the assessed action. On the other hand, ex-post SAT’s evaluate the impacts based on data collected during the time or after an action for sustainable development was implemented.

SAT's could also be classified according to its valuation perspective. In this regard, there exist monetary tools, mostly relying on essential valuation tools to calculate compensation values for the access or deprivation to certain commodity or service, such as willingness to pay, (WTP) or willingness to accept (WTA) (Gasparatos & Scolobig, 2012). It generally includes values judgment regarding the commensurability of sustainability issues. Biophysical tools quantify the natural resources that have been invested during the production of a good or a service. Biophysical tools look at a set of environmental components including soil, vegetation wildlife, hydrology, and biodiversity to link the measured value with an environmental impact. Biophysical assessment tools are intended to prevent the deterioration of ecosystems and to maintain biodiversity, ensuring the consideration of physical, biological, and human components of the analyzed environment. In this respect, biophysical tools employ a rather eco-centric valuation perspective with the role of human preferences becoming obsolete when assessing the policy or action alternatives (Gasparatos & Scolobig, 2012).

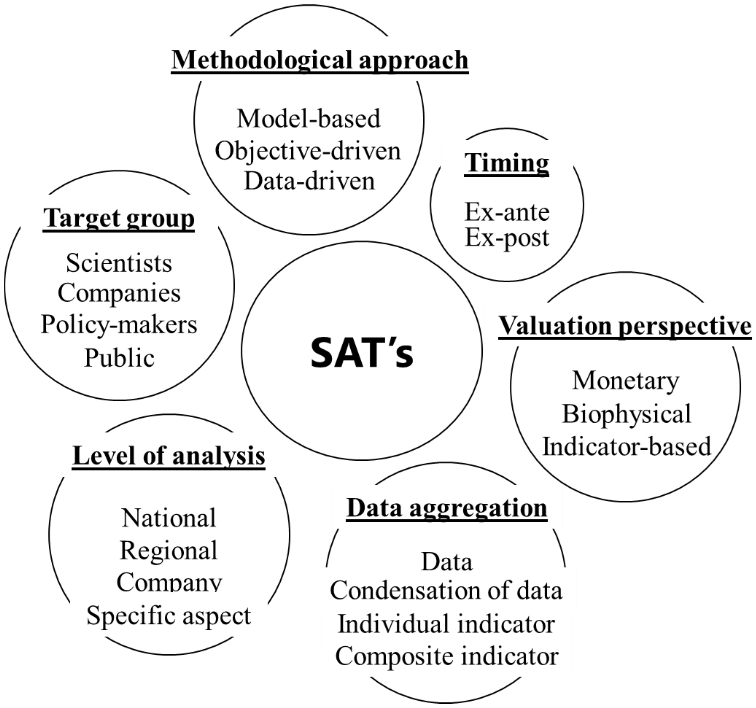

Figure 6.1. SAT's classification categories
Source : (Bélanger et al., 2015; Gasparatos & Scolobig, 2012; Lebacq et al., 2013)

In the same valuation perspective category, we find indicator-based sustainability assessment tools. They generally entail a ladder methodology during indicator selection. Generally, it presents a three or four hierarchical level approach. The most general concept, dimension, is at the top of the hierarchy. In the middle level, sustainability goals are translated to themes or subthemes according to the level of detail required. Finally, at the bottom of the pyramid indicators are measurable variables to evaluate the sustainable performance for the theme or subtheme as applicable (de Olde et al., 2016). Here, the concepts of integration and aggregation emerge. Those are closely related with the data condensation characteristic. Aggregation is the result of combining different components or indicators into one single unit also called a composite indicator. Integration, on the other hand, refers to the use of multiple individual indicators to provide a holistic view of a theme or dimension (Bélanger et al., 2015). However, one of the major criticisms on composite indicators is that the use of weights might disguise the poor performance of one indicator with the good performance of another indicator, causing misleading interpretations and leading to wrong decisions (Goswami et al., 2017).

According to Bélanger et al. (2015), there is a relation between data condensation and target group characteristics. For instance, scientists and technicians are keen on raw data to be able to do statistical analysis and identify every single relation. Contrarily, policymakers and the public that work at regional or upper levels need aggregated data to classify and rank alternatives to make decisions. In fact, decisions are more difficult to make when a great number of indicators are available. Nevertheless, it is important to do not fall into under-representation of what is intended to consider as expected impacts on the policy or action implementation. At the supply chain level, these impacts shall represent the more compelling challenges of the sector at economic, environmental and social dimensions (Chardine-Baumann & Botta-Genoulaz, 2014).

The main purpose of the current model is to determine the structure of a supply chain at the national or regional level, under a wide-industry perspective. It means rather than evaluating the decision of a focal company; the model aims to define in aggregated terms regulatory actions for sustainable development of the sector. An indicator-based model is proposed to this aim. The model evaluates an ex-ante baseline scenario of the supply chain, based on the current state of it and the trending development in the future. Then an evaluation on the implementation of a policy is made, considering the changes in the structure of the supply chain and the implications for the agents belonging to it. Analysis of desired conditions in the sector permits to define norms, standards or thresholds for what an organization's impacts must be; at the economy, environmental and social level, in order to aim towards sustainability. Thus, actual impacts can be contrasted against a reference value. As is stated by (de Olde et al., 2016) that sort of references values could be classified in two, absolute values and relative values. The formers usually represent desirable conditions through targets or threshold, while the latter is derived by comparison of the current value with its initial value or a regional or sample average. Figure 6.2 presents a graphical framework of the model, including the main components of it.

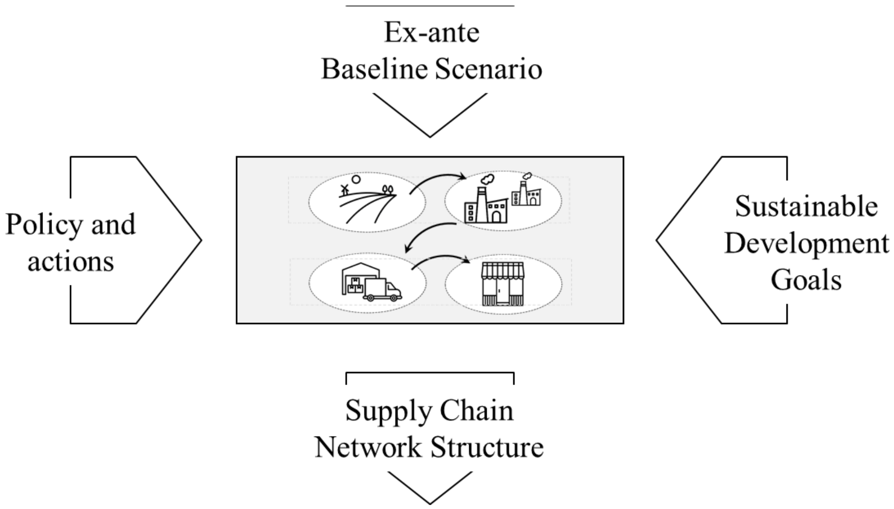

Figure 6.2. Framework of the model

3. Mathematical model

Revisiting the work of (Kannegiesser & Günther, 2014), we present a framework for the assessment of sustainability in supply chains in the long-term. In this particular work, we consider economic, environmental and social impacts for the completely dairy supply chain. The sustainability criteria comprise production, processing and distribution activities. Unlike previous works focusing just on manufacturing activities, the current approach extends its reach to include sustainability criteria at the farm level. The indicators of sustainability are matched with the 17 sustainability goals and 169 targets announced by the United Nations (UN). Thus, it is establishing a context to declare desirable values for those indicators in the future according to the 2030 Agenda for sustainable development (UN General Assembly & United Nations, 2015)**.**

The model considers four echelons of operations named: Production, processors, distributors, and retailers, as shown in Figure 6.3. From the supply chain network design perspective, the model addresses strategical and tactical decisions, defining the zones to milk production, where establishing processing and distribution facilities, which market serves from which locations, as well as the mode of transport required to meet a final aggregate demand in the market.

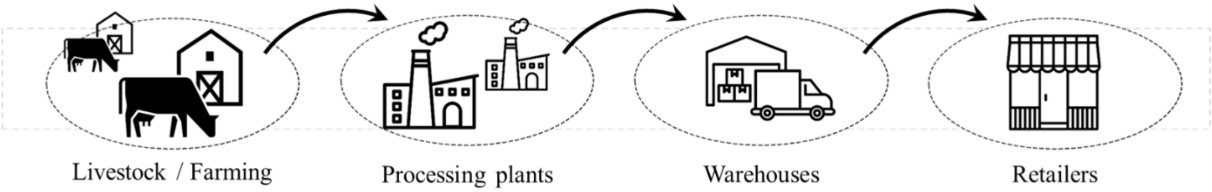

Figure 6.3. Dairy supply chain under study

These kinds of decisions affect the sustainable performance of a company and thus of the whole industry. For instance, allocation of new production capacity or expanding the existent capacity in one region, might increase the carbon footprint through a greater number of emissions coming from production and transportation. However, it could reduce the total operational costs of serving a new growing market and also improves local economy development and labor conditions in the zone.

Unlike most of the previous works in sustainable supply chain design, adopting a focal company point of view, the current approach involves the modeling of the industry-wide supply chain. Thus, a MILP formulation by (Kannegiesser et al., 2015) for a sustainable supply chain network design is reconsidered. The main objective in this optimization framework is to minimize the time in which industry supply chain structures get within acceptable values the total set of sustainability indicators. The framework model is flexible to incorporate multiple sustainability indicators and to evaluate different industry-specific factors affecting the whole supply chain sustainability in the long term.

Since the intention of the model is to propose potential action lines for the sustainable development of the sector in the long-term, a high level of aggregation is considered. For instance, production and processing capacities are modelled on a regional level, as well as demand consumption. The assumption declares that at that level the development of the industry is primarily influenced by some macro-economic factors such a demand, availability of raw materials, rate of employment, technology parameters, global productivity;

aiming to reach an economic stability in the future, rather than the individual competitive behavior of every single company in the market. The elements of the model are defined as follows:

Sets

$Regions\ r \in R$	Nodes in the network representing production, processing and distribution locations.
$Process\ p \in P$	stand for production, processing and storage at different regions.
$Products\ j\ \in J$	include raw material, intermediate products and finished products consumed in performing a process
$Periods\ t \in T$	define division within the time horizon.
$Modes\ m \in M$	represent the different options to the transport of goods through the supply chain.

Subsets

$\{p,r\}\ \in PR$	process-region combination
$p \in$ AP	Agricultural activities
$j \in PO(p,r)$	products produced as output in process *p* at region *r*
$j \in PI(p,r)$	products used as input in process *p* at region *r*
$\{j,r\} \in PF$	product-location combination for final product *j*
$r \in L1(j)$	region where product *j* is produced
$r \in L2(j)$	region where product *j* is used as input
$r \in RP(p)$	region where process *p* is performed
$\{r,s\} \in TL(j)$	transportation lane for product *j* from region *r* to *s* ∊ R

Parameters

Dem_r^t	Demand at consumption region *r* in period *t*
Acm_r^t	Apparent consumption region *r* in period *t*
Cap_{pr}^o	Initial capacity at process *p* at region *r*
α_p	Minimum capacity utilization factor for process *p*
Yf_{pr}^t	Yield factor per unit of process *p* at region *r* in period *t*
Dis_{rs}	Distance between regions *r* and $s\ \epsilon R$
$TrCap_m^o$	Initial capacity for transportation mode *m*
Cap_m^{tr+}, Cap_m^{tr-}	Increase/decrease transportation capacity cost rate of mode m
Lf_m	Loading factor for transportation mode m

Tc_{rs}^{m}	Transportation cost per unit shipped from region r to region s using mode m
Ef_{m}	Emission factor for transportation mode *m* per kilometer
ϕ_{m}	Maximum capacity change rate for transportation mode *m*
PC_{pr}	Processing cost per unit of process p at region r
$Cap_{pr}^{+}, Cap_{pr}^{-}$	Increase/decrease capacity cost rate of process p at region r
Cap_{pr}	Installed capacity cost rate for process p at region r
θ_{pr}	Maximum capacity change rate for process p at region *r*
π	Cost escalation rate
Ed_{pr}	Direct CO_2 eq. emission factor per unit of process p at region r
Ei_{pr}	Indirect CO_2 eq. emission factor per unit of process p at region r
Jb_{pr}	Direct employees in process p at region r
M	Big number

Decision variables

Cpo_{pr}^{t}	Capacity of process p at region r in period t, ($t \neq 0$)
Qpo_{pr}^{t}	Quantity of process *p* executed at region *r* in period *t*
$Cpo_{prt}^{+}, Cpo_{prt}^{-}$	Increase/decrease capacity of process *p* at region *r* in period *t*
Q_{jrs}^{mt}	Quantity of product *j* shipped from *r* to *s* using mode *m* in period *t*
Ctr_{m}^{t}	Transportation capacity of mode *m* in period *t*, ($t \neq 0$)
$Ctr_{mt}^{+}, Ctr_{mt}^{-}$	Increase/decrease transport capacity of mode *m* in period *t*

Dependent variables

C_{po}^{t}	Total processing cost in period *t*
C_{ca}^{t}	Total capacity cost in period *t*
C_{tr}^{t}	Total transportation cost in period *t*
E_{po}^{t}	Total emission caused by processing in period *t*
E_{tr}^{t}	Total emissions caused by transportation in period *t*
Ul_{t}	Total hectares of land use for production activities
J_{t}	Total jobs in period *t*
J_{p}^{t}	Total jobs in process *p* during period *t*
Ld_{t}	Total labor dismissals in production process during period *t*
$Qinf_{rs}^{t}$	Quantity of milk in the informal channel going from region producer r to retailer *j* in period t
C_{cu}^{t}	Cumulative cost up to period *t*
E_{cu}^{t}	Cumulative emissions up to period *t*

Constraints

Calculated variable equations.

Total capacity cost adds up to the cost associated with maintaining a level of capacity to perform processing activities and the cost associated with changing capacity over the time horizon. To include into the model increases in cost future periods, we define a constant growth in function of the time represented by π^t, where $\pi > 1$ is a constant value and t is the index of the time.

$$C_{ca}^{t} = \sum_{\{p,r\}\in PR} Cpo_{pr}^{t} * (Cap_p * \pi^t) + Cpo_{prt}^{+} * (Cap_p^{+} * \pi^t) + Cpo_{prt}^{-} * (Cap_p^{-} * \pi^t) \quad \forall t \in T \tag{1}$$

Total processing cost includes adds up to the cost associated with maintaining a level of capacity to perform processing activities and the cost associated with changing capacity over the time horizon.

$$C_{po}^{t} = \sum_{(p,r)\in PR} \sum_{j\in PO(p,r)} \sum_{m\in M} \sum_{s\in L2(j)} Q_{jrs}^{mt} * PC_{pr} \quad \forall t \in T \tag{2}$$

Total transportation cost includes the cost of all transportation activities required to deliver products from producers to retailers through every tier and the incurred costs when adding or removing transportation capacity for all modes.

$$C_{tr}^{t} = \sum\nolimits_{j\in J, m\in M} \sum\nolimits_{\{r,s\}\in TL} Lf_m * Dis_{rs} * Tc_{rs}^{m} * Qpr_{jrs}^{mt} + Ctr_{mt}^{+} * Cap_m^{tr+} * \pi^t + Ctr_{mt}^{-} * Cap_m^{tr-} * \pi^t \quad \forall t \in T \tag{3}$$

Capacity handling equation

Constraint (4) establishes upper and lower boundaries to the different processes performed in every region in each period. A minimum capacity utilization factor is used to ensure economic feasibility in the process.

$$Cpo_{pr}^{t} * \alpha_p \leq Qpo_{pr}^{t} \leq Cpo_{pr}^{t} \quad \forall \{p,r\} \in PR, t \in T \tag{4}$$

The evolution of the industry considers adjustment on capacity, reduction, and expansion are considered. Migration from one region to another, as well as the construction of new capacity by actual or new competitors, is addressed. Constraint 5 computes the capacity of process *p* at region *r* in period *t*

$$Cpo_{pr}^{t} = Cpo_{pr}^{t-1} + Cpo_{prt}^{+} - Cpo_{prt}^{-} \quad \forall \{p,r\} \in PR, t \in T \tag{5}$$

Since the expansion of capacity requires construction of new facilities, adequation of new soils or the adaptation of the existing ones (facilities and soils), a maximum rate of change per period is used in constraint 6 to limit the growth from period to period.

$$Cpo_{prt}^{+} \leq \theta_{pr} \text{ and } Cpo_{prt}^{-} \leq \theta_{pr} \quad \forall \{p,r\} \in PR, t \in T \tag{6}$$

Output product quantity going from one process to another, coming either, same or different region, must respect the current capacity process installed. Yield factor (Yf_{pr}^{t}) is used to convert units of process into quantity of output products at each stage.

$$\sum_{s\in L2(j)}\sum_{m\in M} Qpr_{jrs}^{mt} + \sum_{sL2(j)} Qinf_{sr}^{t} \leq Qpo_{pr}^{t} * Yf_{pr}^{t} \quad \forall \{j,r\} \in PR, j \in PO(p,r), t \in T \tag{7}$$

Likewise, the quantity of input products delivered to each process in any region, must be enough to perform the intended quantity of process in this region.

$$\sum_{r\in L1(j)}\sum_{m\in M} Qpr_{jrs}^{mt} \geq Qpo_{pr}^{t} * Yf_{pr}^{t} \quad \forall \{p,s\} \in PR, j \in PI(p,s), t \in T \tag{8}$$

Constraint 9 ensures that external demand is met through supply from distribution locations. As a common condition in long-term studies with yearly periods, no inventory is carried out between periods.

$$\sum_{r\in L1(j)}\sum_{m\in M} Qpr_{jrs}^{mt} \geq Dem_{r}^{t} \quad \forall \{j,s\} \in PF, t \in T \tag{9}$$

Moreover, as a condition of agricultural sectors there are some products that do not go through the formal processing, channel, some quantity of product is used for auto-consumption on producing farms, processed in farm, or sold to local informal processors. Equation 10 calculates this value as the difference between the demand in the formal market and the apparent consumption of the product.

$$\sum_{sL2(j)} Qinf_{sr}^{t} \geq Acm_{r}^{t} - Dem_{r}^{t} \quad \forall\, r \in R, t \in T \tag{10}$$

Besides, to consider the possibility of alternatives transport modes, it is necessary to establish limits to the capacity of each mode. Although the availability of resources and the transportation capacity of goods by road is virtually unlimited, the adoption of alternative modes like rail or electrical vehicles are introduced gradually. Hence, equation 11 limits the total freight to the available capacity in each period

$$\sum_{j\in J}\sum_{\{r,s\}\in TL(j)} Qpr_{jrs}^{mt} * Lf_{m} \leq Ctr_{m}^{t} \quad \forall\, m \in M, t \in T \tag{11}$$

Finally, to define changes in transportation capacity from period-to-period equation 12 compute the total capacity per mode per year and equation 13 establish the maximum change from one year to another since the adoption of new technologies implies a step-by-step implementation. Initial transportation capacity (i.e., Ctr_{m}^{0} is given as a parameter to the model.

$$Ctr_{m}^{t} = Ctr_{m}^{t-1} + Ctr_{mt}^{+} - Ctr_{mt}^{-} \qquad \forall\, m \in M, t \in T \tag{12}$$

$$Ctr_{mt}^{+} \leq \phi_{m} \text{ and } Ctr_{mt}^{-} \leq \phi_{m}\ \forall\, m \in M \tag{13}$$

Emissions equations

GHG emissions count allows for direct and indirect emissions sources. Direct emission comes from production and processing activities in each region, meanwhile indirect emissions are associated with the use of energy during the process. Constraint 14 computes the total emissions per period.

$$E_{po}^{t} = \sum_{\{p,r\} \in PR} (Ed_{pr} + Ei_{pr}) * Qpo_{pr}^{t} \quad \forall t \in T \tag{14}$$

Another source of GHG emissions is transport activities between stages of the network. Equation 15 determines the total emissions according to the volume of product sent among facilities and the transportation mode for each period.

$$E_{t}^{tr} = \sum_{j \in J} \sum_{m \in M} \sum_{\{r,s\} \in TL(j)} Ef_{m} * Dis_{rs} * Lf_{m} * Qpr_{jrs}^{mt} \quad \forall t \in T \tag{15}$$

Use of land equation

Since pressure over the productive systems is a cause of biodiversity loss, deforestation, soil compaction and eroding. Constraint 16 adds up the total number of hectares used at the first stage of the chain.

$$Ul_{t} = \sum_{r \in RP(p \in AP)} Cpo_{pr}^{t} \quad \forall t \in T \tag{16}$$

Employment equation

Constraint 17 computes the total number of jobs in each period offered at various stages of the supply chain.

$$J_{t} = \sum_{\{p,r\} \in PR} Jb_{pr} * Qpo_{pr}^{t} \quad \forall t \in T \tag{17}$$

Equation 18 calculates the number of labor dismissals at agricultural level. Productive transformation of agriculture industry is often accompanied by labor dismissals at agriculture productive units.

$$Ld_{t} = \sum_{p \in AP, \{p,r\} \in PR} Jb_{pr} * (Qpo_{pr}^{0} - Qpo_{pr}^{t}) \ \forall t \in T \tag{18}$$

Cumulative equations

As a part of the optimization approach, we consider cumulative cost and cumulative emissions up to period *t*. Unlike other studies limiting GHG emissions period by period, this approach considers the cumulative nature of GHG emissions. As stated by (Rhys, 2011) is the cumulative concentration of GHG that drives future climate disturbance, - the stock rather than the flow. Equation 19 and Equation 20 present total cumulative cost and total cumulative emission up to period *t*, respectively.

$$C_{cu}^{t} = \sum_{t=0}^{t \in T} C_{po}^{t} + C_{ca}^{t} + C_{tr}^{t} \tag{19}$$

$$E_{cu}^{t} = \sum_{t=0}^{t \in T} E_{po}^{t} + E_{tr}^{t} \tag{20}$$

To use time to sustainability optimization approach to construct the ex-assessment model to the application of policies, the following sets of elements are added to the model.

Sets

$Key\ indicators\ k \in K$	set of indicators selected to evaluate sustainable development {cumulative operational costs, CO_2 emissions stock, use of land, total layoffs}

Parameters

θ_{p}^{ALT}	Maximum capacity change rate for process *p* in the alternative scenario
ϕ_m	Maximum capacity change rate for transportation mode *m* in the alternative scenario
ψ_{k}^{+}	Upper limit of the sustainable value for indicator k
ψ_{k}^{-}	Lower limit of the sustainable value for indicator k
G	Big number

Variables

τ_t	$\begin{cases} 1, if\ at\ least\ one\ key\ indicator\ is\ out\ of\ sustainable\ range \\ 0, otherwise \end{cases}$
KPI_{kt}	Actual value of KPI *k* in period *t*
π_{kt}	Total deviation respect to acceptable value of KPI *k* in period *t*

Time to sustainability constraints

At the time of the baseline scenario ($t = 0$), at least one indicator is considered as unsustainable. Hence the value of the variable $\tau_0 = 1$.

$$\tau_0 = 1 \tag{21}$$

τ_t is equal to one if at least one of the key performance indicators has not reached the target value, otherwise it will be equal to zero. During the following periods, the differences between the current value of the indicators and their target are accounted by π_{kt} in equation 22. Here KPI_{kt} corresponds to the value of key indicator *k* in period *t*. This value is computed using equations (16), (18), (19) and (20) for use of land, layoffs, cumulative cost and cumulative emissions, respectively.

$$\pi_{kt} \geq KPI_{kt} - \psi_k^{+} \quad \forall\, k \in K, t \in T \tag{22}$$

Constraint 23 ensures that once all indicators have achieved the targets, it must be preserved over incoming periods within the planning horizon.

$$\tau_t \leq \tau_{t-1} \quad \forall\, t \in T\colon t > 0 \tag{23}$$

A key performance indicator is considered sustainable during a period if the actual value of the indicator k is under the defined sustainability target value. Hence, τ_t still being equal to one until the differences between the current value and the target are less or equal than zero.

$$G * \tau_t \geq \pi_{kt} \quad \forall\, k \in K, t \in T \tag{24}$$

The objective function is to minimize the number of periods until all indicators fall below the target value.

$$\min Z = \sum_t \tau_t \tag{25}$$

4. Optimization Strategy

The current section describes the optimization strategy to the definition of the ex-ante assessment model. The evaluation requires the definition of a baseline scenario in the long-term. Then results yielded in the first execution are inputs to the definition of objectives in the second scenario where policies and goals are set, considering key performance indicators in the three dimensions of sustainability. Figure 6.4 shows a graphical representation of the optimization strategy. Input data contains production, processing, storage and transportation capacities per region at the beginning of the evaluation period, among the required parameters presented in the previous section required to initialize the model. This data is used to solve a minimizing cost optimization model, and the results are input to the second optimization strategy. Optimization strategy 1 and 2 are described below.

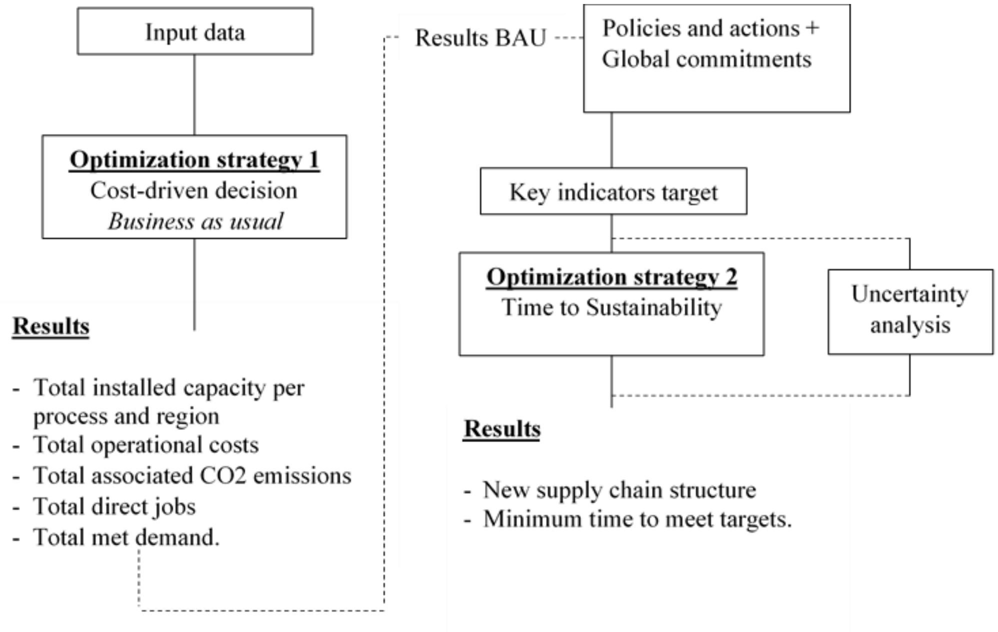

Figure 6.4. Optimization strategy

<u>Optimization Strategy 1 - Baseline Scenario</u>: *Cost-driven supply chain network decision-making*

The first optimization strategy, known as B*usiness as Usual* scenario (BAU), consists of defining the structure of the supply chain in the long term, based on the total operational costs. To this aim, the model includes equations (1) to (20), being equation (19) the objective function. The single objective function includes the total processing and the total transportation costs.

The model considers processing activities as black boxes. Thus, the capacity of a facility can be expressed as a single value limiting the output flow for each product at this facility. The facility location decisions at plants and warehouses are guided by two types of costs. Fixed costs and processing costs, the formers are fixed while the latter depend on the production level of the corresponding facility. Transportation activities assume full truck load and its cost's function is assumed to be linear.

From the results of the first optimization strategy, we get the evolution of the installed capacity per process in each region, as well as the total operational cost during the time horizon. Moreover, the results show the value of the different sustainability key indicators in the business-as-usual scenario, such as, CO_2 emissions stock, direct jobs, informality, among the others mention in Chapter 5 (see Table *5.4.* Sustainability indicators and SDG's considered in the ex-ante sustainability assessmentTable 5.4). These values are important to compute the target values used in optimization strategy 2.

<u>Optimization Strategy 2 - Alternative scenario</u>: *Time to sustainability approach*

The time to sustainability approach is a recent approach, that appears to be relevant for the evaluation of policies in the long-term industry context and the supply chain network structure. This optimization strategy seeks to minimize the number of periods until all key indicators reach a sustainable value or target (a value between its corresponding upper and lower limits). As is stated in (Kannegiesser & Günther, 2014), defining targets for every indicator requires to define a baseline values. In the current approach, targets are established considering the results yielded by the business-as-usual scenario in the first optimization strategy and national objectives for the sector. In this stage, the implementation of policies affects the development of the supply chain, adding new criteria for sustainable development. The model comprises equation (1) to (25), where equation (25) is the objective function.

As introduced by (WRI & WBCSD, 2014), the principles of relevance, transparency, completeness, consistency, accuracy, conservativeness are applied to the projection of the expected results. Besides, it is important to consider uncertainty as a relevant factor at developing ex-ante assessment model (IWR, 2016). Since the results might be associated with different variables, it is necessary to evaluate uncertain conditions on the results, to provide more trustable results. For instance, policies might be evaluated in environments with different initial conditions, having effect on the overall result of the application, in this case results derived by the application of the policy might be over or underestimated.

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Chapter 7 TTS Results and Analysis

The content of this chapter is part of the paper submitted for publication as: Moreno-Camacho, C. A., Montoya-Torres, J. R., Jaegler, A., Gondran, N. “Agrifood Supply Chain Network Design Under Sustainable Development Policies”. *European Journal of Operational Research*

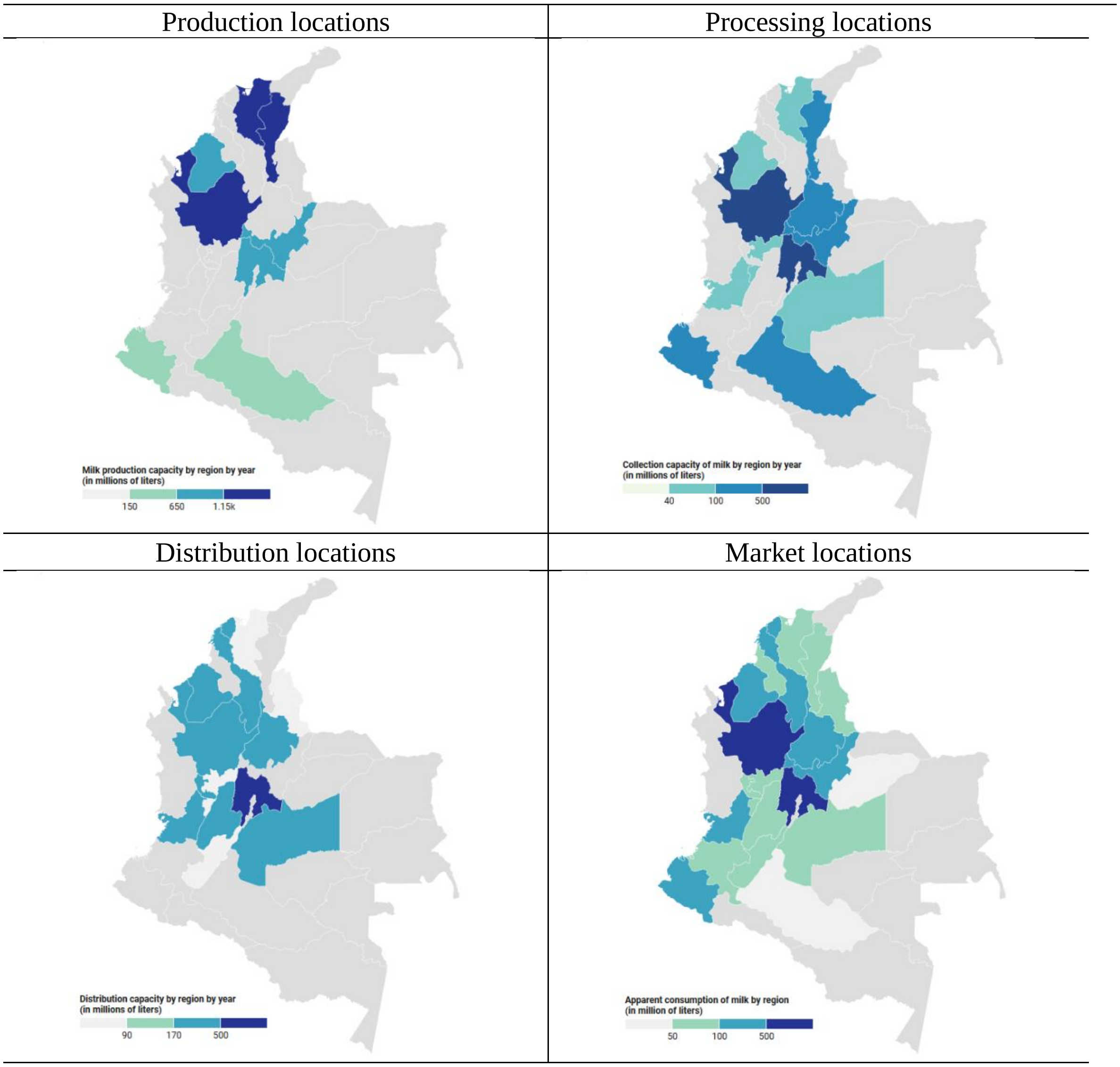
This chapter presents the results from the execution of the model described in Chapter 6 and applied to the case study introduced in Chapter 5. First, the chapter presents a summary of the data collected to the case study and the experimental context. Using an ex-ante baseline scenario approach, the model considers the impacts at economic, environmental and social levels on the structure of the dairy supply chain when a national policy aiming to meet international commitments facing climate change is implemented. Since, the expected results of the policy may be influenced by implementation parameters, a sensitivity analysis is carried out, considering uncertainty in the efficiency of the implementation.

1. Data collection

First, worth mentioning that to model industry-wide supply chains, process capacities have been aggregated by region. Although arguably it brings an inevitable degree of limitation to the model, a very fine detail description it is neither desired nor practical on developing model evaluation in a long-term study. Moreover, since the purpose of the model is to work as a sustainability assessment tool for the evaluation of policies, the level of detail at regional level is appropriate to this goal. In this regard, capacities have been aggregated by region in each stage of the chain. Figure 7.1 presents a wide view of the location and capacities of production, processing, distribution and consumption all over the Colombian territory.

Production locations:

The primary production process refers to the milk production system in farm or dairy herd units, i.e. in dairy or dual-purpose farming. Highlands in the central region of the country, including Cundinamarca, Boyacá, Nariño and the northern region of Antioquia are characterized by specialized dairy systems. Dual-purpose farms are mainly located in the Magdalena and Cauca river valleys, the Atlantic Coast and the Eastern lowlands. Although production of milk take place all over the country the model considers eight departments (political administrative divisions) which add near the 80% of the total national production, according to the Colombian national agricultural survey (ENA, by its acronym in Spanish) (DANE, 2017). This selection includes four specialized dairy regions (Antioquia, Cundinamarca, Boyacá and Nariño) and four regions managing dual-purpose cattle (Magdalena, Caquetá, Cesar and Córdoba). The two systems differ both in their productivity and in their production costs. Table 7.1 presents some relevant data for each region including the average productivity rate by animal and area as well. The cost of producing milk in each region is shown in the fifth column. It is worthy to note how dual-purpose systems have lower productivity rates per animal, higher use of land and lower production cost as well.


Production locations

Processing locations

Distribution locations

Market locations

Figure 7.1. Supply chain locations and capacities
Source: Data from (MADR & UPRA, 2018), (USP, 2019)

Lactation cycle is an important factor within the milk producing systems. Considering this issue, a percentage of current milk producing cows is calculated for each milk-production system (i.e., specialized dairy system or dual-purpose system). According to the ENA 2017, the average of milking cows in specialized dairy systems is around 55% of the total cows in production age, while in dual-purpose this percentage is around 40%. It is an important factor not only for the account of direct emissions from cattle but also for the computation of use of land. The total number of milking cows per region, the yearly production capacity by region and its corresponding stocking rate are shown in Table 7.2.

Table 7.1. Production systems characterization

Location	**Classification**	**Productivity rate*** (l/head/day)	**Area yield†** (l/ha/year)	**Milk producing cost⸙** (USD/l)
Antioquia	Specialized dairy system	11.4	3065.5	0.22
Boyacá		7.6	3107.0	0.21
Cundinamarca		11.3	3538.0	0.21
Nariño		9.8	1878.0	0.22
Caquetá	Dual-purpose system	4.0	751.0	0.22
Cesar		3.1	1099.0	0.18
Córdoba		2.9	687.0	0.15
Magdalena		4.0	1123.0	0.18

* Encuesta Nacional Agropecuaria. DANE, 2017

† Unidad de Planeación agropecuaria, UPRA, 2019

⸙ Costos de producción. Fedegan 2019. 1

Table 7.2. Animal load and production capacity per region

Location	**Stocking rate*** **(**head/ha)	**Milking cows†** (head)	**Yearly production capacity†** **(**in liters**)**
Antioquia	0.9	605,844	2,526’479,296.6
Boyacá	1.2	251,401	693’936,009.8
Cundinamarca	1.2	322,787	1,336’979,540.3
Nariño	1.6	83,037	295’628,401.9
Caquetá	0.5	158,245	232’429,298.8
Cesar	0.5	250,957	287’640,792.1
Córdoba	0.5	270,787	290’197,266.9
Magdalena	0.5	293,294	437’964,722.0

* Data from (Fedegan, 2014)

† Data from DANE, 2017

An additional point to considered is the cost of land at different regions. Since upland soils regions often have improved conditions for the development of several sowing activities, they also have advantages to access to large markets, it cost is higher than the cost for low tropical lands. Thus, the price paid per area for livestock development in the central region of the country is usually higher than that paid in coastal areas. Table 7.3 presents the cost per thousands of hectares in each region in thousands of dollars. The value is computed using the distribution of land and its real estate appraisal. The cost of increasing capacity at any region includes the material and manpower necessary to adapt a hectare or a thousand of them for the cattle activity. It includes installation of the fence, adequacy of the grass, labor, and materials. Meanwhile the cost of decreasing capacity only counts for the labor required to retire fences. Finally, in the third column, the table presents the number of employees by hundreds of animals in the two different farming production systems (i.e., specialized dairy and dual-purpose).

Table 7.3. Cost of land and employment capacity

Location	**Cost of land*** (‘000 USD/ ‘000 ha)	**Increase capacity cost†** (‘000 USD/ ‘000 ha)	**Jobs⸙** (# of jobs/ 00 of cows)
Antioquia	236.52	137.33	8
Boyacá	304.41	137.33	8
Cundinamarca	263.13	137.33	8
Nariño	318.67	137.33	8
Caquetá	296.25	137.33	5
Cesar	243.25	137.33	5
Córdoba	278.92	137.33	5
Magdalena	213.39	137.33	5

* Atlas mercado de tierras, (UPRA, 2019)

† (Gutiérrez et al., 2018) and (Giraldo, 2008)

⸙ Calculated from Encuesta Nacional Agropecuaria. (DANE, 2017)

Regarding GHG farm emissions, we use data from studies in Colombia comparing different conventional production systems in tropical highlands as in tropical lowlands with silvopastoral systems strategies. Most of the studies are developed by the Center for Research on Sustainable Agricultural Production Systems (CIPAV by its acronym in Spanish). A cradle to farm gate approach is used to quantify the emissions in these farm systems. Table 7.4 presents a comparison of the values of GHG emissions for silvopastoral Systems (SPS) and Conventional System (CS) by functional unit in high lands, dry tropic and acidic soils. These values come from (Rivera et al., 2016) they are in the range of other studies like (Chará et al., 2017b; Rivera et al., 2015).

Table 7.4. GHG emissions factors at farming level
Source: (Rivera et al., 2016)

	Dairy systems – Colombia					
	High fields (<2k mamsl)		Dry tropic		Acidic soils	
	ISPS	CS	ISPS	CS	ISPS	CS
Kg CO_2 eq./ Kg of milk	1.47	1.56	2.16	4.15	1.54	1.68
Kg CO_2 eq./ Kg of milk (FPCM)	1.87	2.05	2.06	4.08	1.60	1.78
Kg CO_2 eq./ Kg of milk (ECM)	1.52	1.69	2.06	4.08	1.60	1.78

mamsl : meters above mean sea level

Processing locations and distribution centers:

According to MADR the formal collection of milk during 2019 did took place in 24 departments in Colombia. Twelve of them sum up to the 95% of the total collection which is about 3 billion liters per year. Table 7.5 shows the total collection capacity by department.

Table 7.5. Collection capacity per region

Location	**Collection Capacity*** **(**liters)	**Percentage** (%)	**Cumulative percentage** (%)
Antioquia	1,183’537,285.0	37.33	37.33
Cundinamarca	886’910,198.8	27.97	65.30
Boyacá	251’490,306.1	7.93	73.23
Cesar	137’750,805.0	4.34	77.58
Nariño	121’448,620.0	3.83	81.41
Caquetá	107’498,029.0	3.39	84.80
Santander	76’397,970.2	2.41	87.21
Caldas	64’022,658.0	2.02	89.23
Magdalena	48’373,517.0	1.53	90.75
Valle del Cauca	48’141,213.5	1.52	92.27
Córdoba	45’419,409.1	1.43	93.70
Quindío	42’080,837.0	1.33	95.03
+12 departments	157’513,325.9	4.97	100
Total Capacity	3,170’584,174.6		

* Unidad de seguimiento de precios de leche. MADR 2019

Regarding the contribution of this stage to GHG emissions, we consider direct and indirect emissions. To this aim some sustainability reports from different processing companies were consulted (Alpina, 2018; Alquería, 2019). Table 7.6 shows the marginal values of GHG emissions by tons of final product. The factor considered to transform energy into CO_2 eq. units is 164.38 g CO_2 eq./kWh. This factor corresponds to the updated factor of the Colombian energy matrix which allows companies in the country to calculate the carbon footprint associated with electricity consumption, it was determined by studies carried out by the Colombian Ministry of Mines and Energy, the Mining and Energy Planning Unit (UPME, 2019)

Table 7.6. GHG emission factors for processing process

	Direct emissions	Indirect emissions
Ton CO_2 eq./ Ton final product	0.17	0.138

Consumption locations:

Consumption departments were defined considering the presence of the principal retailer company in Colombia. Grupo Éxito has presence in 22 out of the 32 departments in Colombia. The list includes Antioquia, Atlántico, Bolívar, Boyacá, Caldas, Caquetá, Casanare, Cauca, Cesar, Córdoba, Cundinamarca, Huila, Magdalena, Meta, Nariño, Norte de Santander, Quindío, Risaralda, Santander, Sucre, Tolima, and Valle del Cauca. As is stated in previous studies, two of the main variables describing the behavior of milk consumption are population and apparent consumption, which is lastly related with population incomes (FAO, 2014). Thus, in this work, we use the very same variables to estimate the demand for the upcoming years. Data include apparent consumption estimation for the whole set of dairy products including, pasteurized milks, sour milks products, sweetened milks, butter and cream, and milk powder. The annual growth is based on previous years' growth rate and is a conservative estimate. A list of the data sources to the validation of the model is presented in Appendix 1.

2. Experimental context

The current section shows the conditions for the construction of the ex-ante baseline scenario and the alternative scenario. Table *7.7* presents the value and considerations of the different parameters involved.

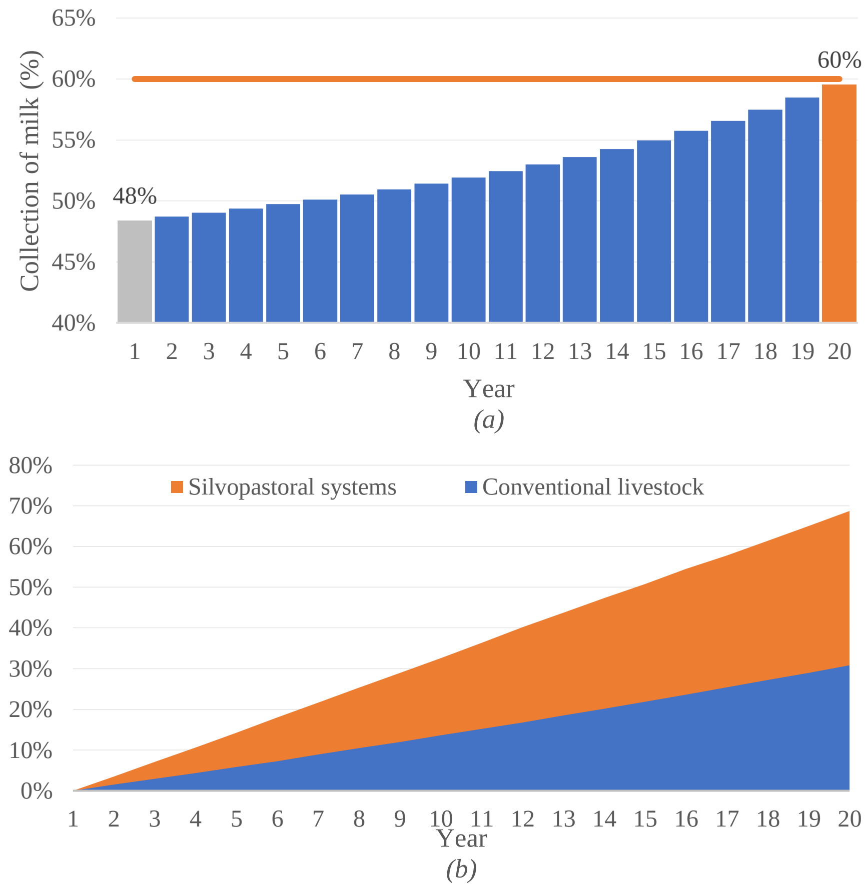
Table 7.7. Experimental context parameters

	Baseline scenario	**Alternative scenario**	
Decision driver	Total cost	Time to sustainability	
Time horizon	20 years	20 years	
Key indicators			**Guidelines**
Total cost	Objective	≤ 1.05 Baseline Total cost	
Cumulative GHG emissions	Non-restricted	≤ 0.8 Baseline GHG emissions	NDC Colombia (MADS, 2015)
Use of land	Non-restricted	≤ 0.7 Baseline Total hectares	PAS GEI SA (MADR, 2017)
Layoffs	Non-restricted	≤ Baseline Layoffs	PAS GEI SA (MADR, 2017)
Formal collection of milk	0.48 to 0.6 collection of milk	0.48 to 0.6 collection of milk	PIGA SL (Leiva B., et al., 2016)
Scenario drivers			
Silvopastoral systems	+ 5600 ha/year	+ 28000 ha/year	
Electric fleet usage	-	+ 200 trucks/year	
Consumption pattern	Forecast	Forecast	
Farm Productivity	Trend	Trend	

The Baseline scenario represents the *Business As Usual* (BAU) decision, in which the economic factor takes the lead. In this scenario, all sustainability indicators are non-restricted, and the minimum total cost guides the final decision. On the other hand, the Alternative scenario is driven by the minimum needed time to obtain acceptable values for every sustainability key indicator. To this purpose and considering national and sectorial plans for developing the agri-food sector, the livestock sector, and the dairy industry, an acceptable cap is imposed over each key indicator. For example, since the Intended National Determined Contributions presented by Colombia to the Conference Of the Parties (COP) establishes an unilateral and unconditional commitment for the reduction of at least 20% of GHG emissions (MADS, 2015) in comparison to a BAU scenario, we define, for the alternative scenario, a cap of 80% on the cumulative GHG emissions in reference to the Baseline Scenario. The same approach leads to the definition of boundaries to the rest of the key indicators. The international agreements, national or sectorial plan considered to the definition of caps are listed in column four of Table 7.7. A 20-year horizon is considered, this period exceeds the term for compliance with the CMNUCC agreements and is in line with the strategical development plan for the Colombian livestock sector.

Noticeable the baseline scenario and the alternative scenario differ from the capabilities of the development of the sector. On the one hand, the baseline scenario depicts the current state of the sector with a low yearly transformation rate of silvopastoral systems and no use of an electric fleet. On the other hand, the Alternative scenario represents the large-scale adoption of mitigation and adaptation practices in the industry led by the scaling up on the appropriation of silvopastoral systems (Tapasco et al., 2019) at the agricultural level and the use of electrical fleet for distribution activities. Other scenario drivers, such as consumption patterns and farm productivity, remain interchangeable between the scenarios, but not static.

In this respect, the collection of milk is included in the model as a fixed pattern for both scenarios. It defines a minimum acceptable level for the formal collection of milk. Simultaneously, it makes the baseline and alternative scenarios comparable between them, concerning the economic, social, and environmental indicators for sustainable development in the dairy industry. Hence, a conservative per year growth takes the national collection level of milk from 48% in year 1 to about 60% in year 20. These values are within the range presented by other ongoing prospective studies of the dairy sector (MADR & UPRA, 2018). Moreover, there are external variables influencing the development of the dairy sector, such as, livestock enhancing, genetic development, crossbreeding activities, and a construction of know how through experience, which are not included into the model. To consider the changes caused by these variables a productivity trending factor has been stablished, according to a conservative historical behavior. These factors are usually established to consider optimistic, pessimistic and trending scenarios for the sector (MADR & UPRA, 2018). The parametrized behavior for these conditions is presented in Figure *7.2*.



(a)

(b)

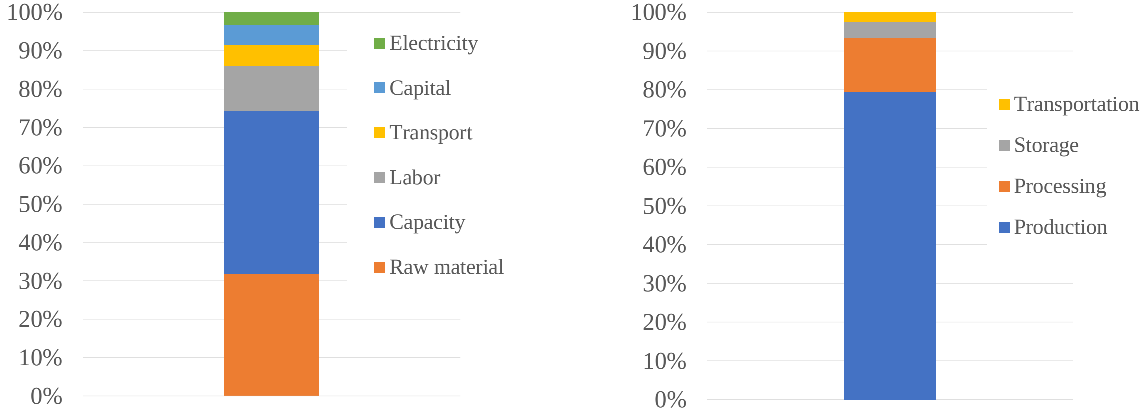
Figure 7.2. (a) Collection of milk, and (b) farm productivity over the time horizon

Figure 7.2b presents the percentual productivity increase by area for the two different production systems, namely, silvopastoral systems and conventional livestock. In this respect, productivity per hectare might increase by about 30% for conventional systems and more than 60% for silvopastoral systems over 20 years. These values are in the range of previous studies representing the sector's trending behavior and the expected improvements at implementing silvopastoral systems (J Chará et al., 2019; MADR & UPRA, 2018).

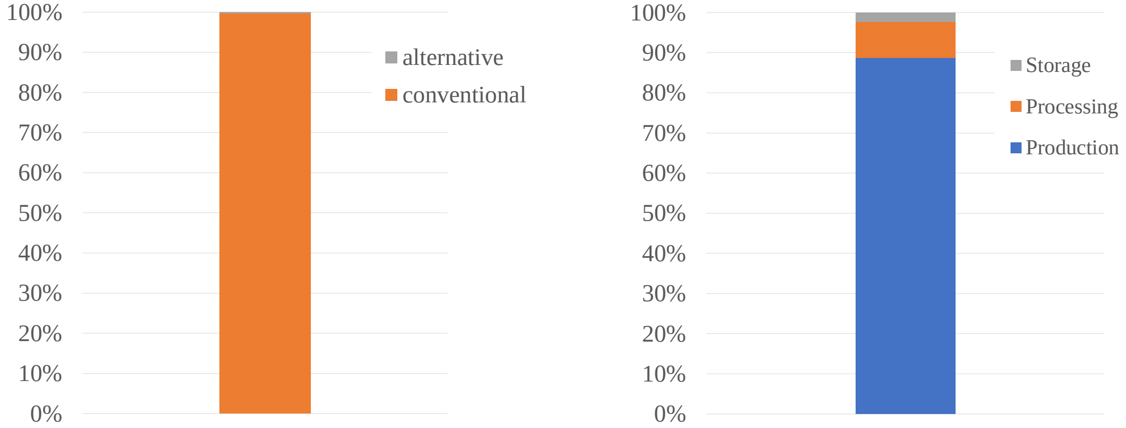
3. Results

3.1. Baseline scenario cost drivers

The model describes the behavior of the supply chain during a twenty years horizon when the decisions are guided by the total operational cost, with the conditions listed to the baseline scenario in Table 7.7.



(a) Cost structure *(b)* Emissions sources



(c) Land Use *(d)* Employee sources

Figure 7.3. Costs structure, GHG emissions sources, use of land, and employment distribution conditions in the baseline scenario

The first optimization run provides a better understanding of the cost structure of the supply chain, the sources of GHG emissions, the use of land, and the category of employment in the sector as presented in Figure 7.3. Realistic cost structures may be a relevant factor in considering the validity of the results.

Moreover, the relative contribution of each factor to the achievement of the objectives is crucial and will affect the evaluation in the alternative scenario.

Results show the characteristics of the supply chain, where capacity cost and raw material represent about 30% and 40% of the supply chain's total costs, respectively. High costs of land in tropical highlands, where specialized dairy production occurs, are the main contributor to the capacity category. Further, the raw material cost is well known to be one of the highest contributors to the total production cost; previous studies have shown that it accounts for about 80% of the production stage costs (Akin & Cevger, 2019).

Regarding contributions to GHG emissions in the sector, transportation activities represent less than 5% of the sector's total emissions. In comparison, farming activities account for nearly 80% of the total and transformation activities at the industrial represent about 15%. These results are aligned with what was found by Notarnicola et al. (2017), regarding the contribution of food producers to overall environmental performance in food supply chains. Additionally, it also stresses that non-aligned mitigation activities coming from the industrial partner may undoubtedly achieve an important effect on the overall performance of the supply chain but be insufficient to achieve sustainable values for the whole sector. That condition should be a trigger for the definition of collaborative mitigation activities in the agri-food sector, where the impact of agricultural activities has the most considerable contribution.

The second key indicator related to the environmental performance of the supply chain is the use of land. Figure *7.3*c shows that almost all of the milk production is based on extensive pastures, the conventional system for milk production in the country in the initial state. Although some projects have encouraged the adoption of silvopastoral systems in the livestock sector, their development is at a primary stage, and nowadays, it represents only near to the 1% of the total land used for the production of milk, including both specialized dairy and double purpose farms (Tapasco et al., 2019).

Additionally, regarding employment, milk production adds up to about 85% of the total employees of the supply chain, while the remaining percentage is at the industrial tier in processing and storage activities. This distribution reflects what was mentioned before regarding the imbalance in the sector, in which there are many producers but a small number of buyers. This is a common scenario in developing countries, where many farm smallholders contribute to the supply of food for regions. Moreover, it highlights the importance of the sector at the social level as a trigger of economy development in rural areas and the need for all-inclusive policies to transform the agricultural sector.

Worthy of note that from the initial stage of the supply chain and its current conditions, it is possible to infer that alternative scenarios considering only mitigation options at the industrial level might not be practical, neither enough to meet sustainable values. For instance, an alternative scenario considering only electric vehicle fleet usage is not practical since even the total reduction of transportations emissions is not enough to reach the sector's sustainable goal. Besides, it would not modify land use, which is one of the key sustainability indicators. For that reason, the proposed alternative scenario must consider all mitigation strategies at once.

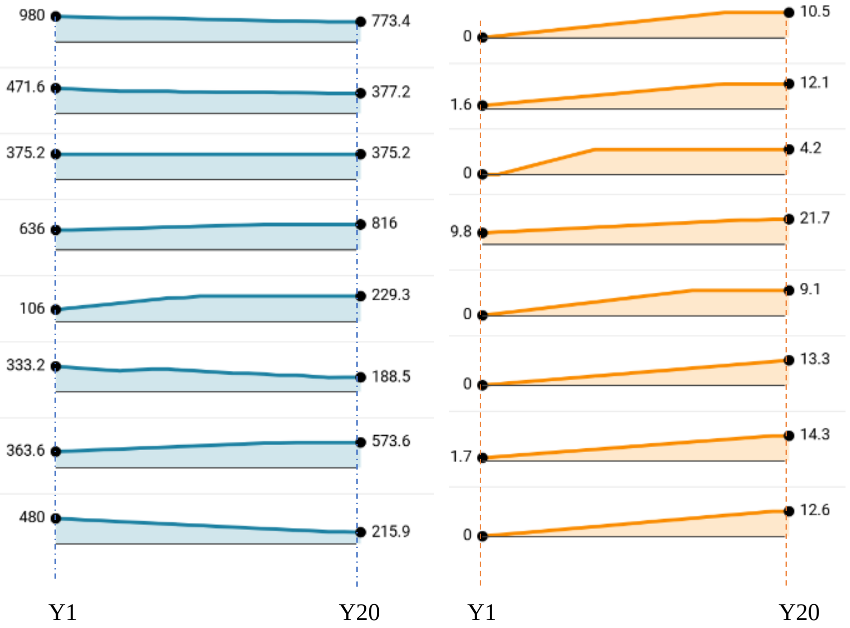
3.2. Baseline scenario capacities

Table 7.8 presents a summary of the changes in milk production capacity in the baseline scenario for each one of the eight regions in the study case. The total number of hectares dedicated to conventional livestock for milk production reduces by about 5%. It goes from 3,758,685 hectares in year 1 to 3,646,930 hectares in year 20. Conventional livestock system reduces its capacity in all specialized dairy regions. While it presents expansions in three out of four low tropical land regions, where dual purposes farms are located.

At the same time, the number of hectares transformed to silvopastoral systems goes up in all the regions, reaching a total of 97,780 hectares. There are not extreme differences between specialized dairy and dual-purpose regions on the appropriation of silvopastoral systems. At the end, the total number of hectares transformed represents around 3% of the total area utilized. Considering the gains and losses in the total land area, the model achieves a reduction of slightly over 3% of the total occupied area, mostly led by considerable reductions of fields in the high tropical lands, associated with specialized dairy farms.

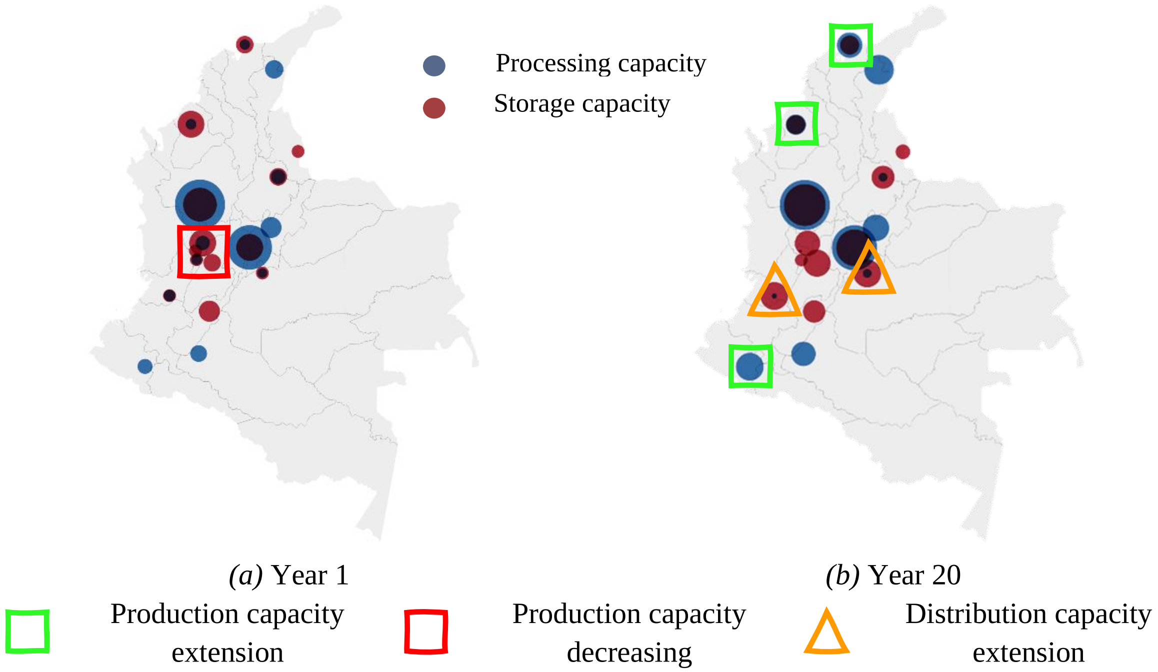
This effect is mostly explained by the high cost of the tropical highlands, which maintains an advantage for developing dual-purpose activities in the tropical lowlands. Besides, it is worth pointing out that the reduction in the number of farms is a well-known consequence of the productivity transformation of agricultural sectors (Cadena et al., 2019).

Table 7.8. Production capacity in the baseline scenario (ha)



Region	Conventional		Silvopastoral systems		Farm type
	Y1	Y20	Y1	Y20	
Antioquia	980	773.4	0	10.5	Dairy
Boyacá	471.6	377.2	1.6	12.1	Dairy
Caquetá	375.2	375.2	0	4.2	Dual purpose
Cesar	636	816	9.8	21.7	Dual purpose
Córdoba	106	229.3	0	9.1	Dual purpose
Cundinamarca	333.2	188.5	0	13.3	Dairy
Magdalena	363.6	573.6	1.7	14.3	Dual purpose
Nariño	480	215.9	0	12.6	Dairy

Figure *7.4* presents a comparison between the initial state of the network and the final situation of it regarding the allocation of processing and storage capacities. The size of the circle is associated with the amount of installed capacity in each region. In broad sense, processing capacity increases by 29% over the time horizon. The most notable changes are Cordoba, Magdalena, and Nariño, where it is at least doubled (*green squares in* Figure *7.4b*). Other regions like Caldas and Quindío suffer a total reduction in capacity until the disappearance of the processing industry (*red square in* Figure *7.4a*). Concerning storage capacity at distribution centers, it increases around 27% during the 20 years window. The most significant variations are presented in Meta and Valle del Cauca, where the storage capacity grows up to four times with respect to the year 1(*orange triangles in b*).



(a) Year 1 *(b)* Year 20

Figure 7.4. Evolution of processing and storage capacities from (a) Year 1 to (b) Year 20

3.3. Baseline scenario Employment

Figure 7.5 presents the distribution of employees in the initial and the final situation. As a result of the decline of capacity in the conventional production of milk, there is a reduction in the number of employees at the agricultural level, partially compensated with the transformed silvopastoral areas' jobs. However, over the twenty years, about 19% of the initial jobs in agriculture are lost. It means about forty thousand employees at the agricultural tier must be generated in other agricultural activities to compensate for the loss in the dairy sector. This situation requires the promotion of alternatives agro-business, which a political level must include financial programs aimed at training and reorganization of farmers and their productive units.

Regarding the industrial tiers, including processing and storage activities, around fifteen thousand new employees are created, representing a growth of about 2.6% by year in the sector. This outstanding growth is related to the systematic rise in the formal collection of milk at all production regions, supposing a more significant amount of milk for processing and distributing.

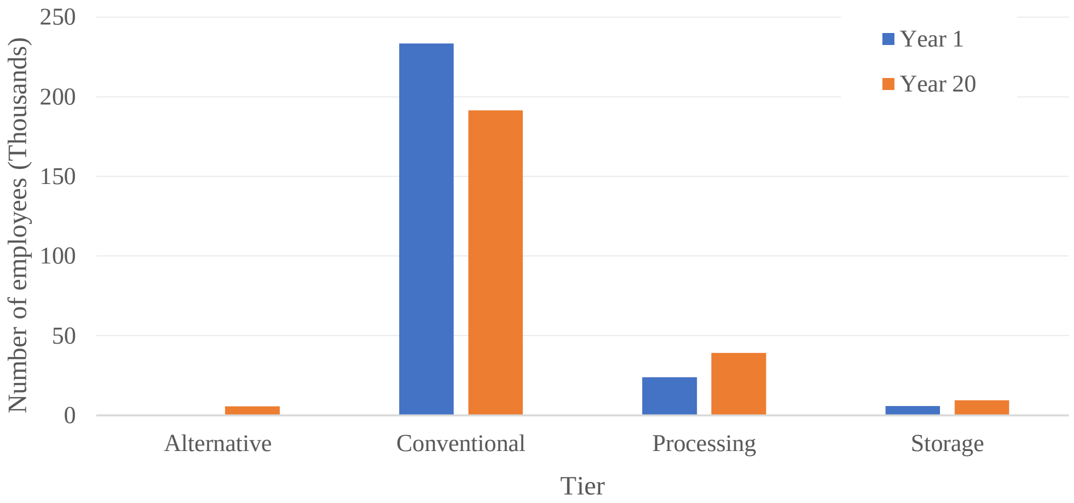


Figure 7.5. Employment creation in the baseline scenario

The following section presents further analysis of cost, emissions, and employment results in the baseline scenario. Next section presents a comparison between baseline and alternative scenarios and analyze the capabilities of the industry to achieve the imposed sustainable goals.

3.4. Alternative scenario

The current section presents the results of the alternative scenario. In this scenario, each key indicator is given a target related to national or sectoral objectives. The model aims to calculate the minimum number of years in which all key indicators reach this sustainable value. To this purpose, the model considers a list of scenario drivers, as presented above in Table 7.7.

Implementation of nationally appropriate mitigation actions (NAMA's), and the productive transformation to the sector aiming to meet sustainable measures, demands cooperation between stakeholders in the promotion of policies that assist in the transition, and investments from actors of the supply chain. Therefore, considering the sector's competitiveness over the time horizon, the total cost in a specific year in the alternative scenario cannot exceed by more than 10% the cost of the same year in the baseline scenario. Additionally, the total cumulative cost at the end of the year 20 cannot exceed by 5% the base scenario's total cumulative cost. That condition brings attention to the need of investing money to the development of green initiatives. However, boundaries must be established in this regard, otherwise, a friendly-environment development could lead to a loss of competitiveness, which is not sustainable (Kannegiesser & Günther, 2014).

3.5. Cumulative GHG emissions versus costs

The alternative scenario considers scaling up silvopastoral systems and using an electric vehicle fleet for distribution activities. Although these actions might have positive economic benefits, in the long run, initial investments are a barrier to its adoption. *Figure 7.6* shows how GHG emissions could significantly reduce in the alternative scenario, slightly increasing the total costs. Here, a higher development rate of silvopastoral systems led quickly to considerable reductions. For instance, after three years, a 10% reduction in accumulated emissions is achieved; additional improvements take longer, and the proposed 20% reduction in total cumulative emissions is achieved 15 years later, in period 19. Once the goal is reached, the model ensures compliance in the subsequent periods.

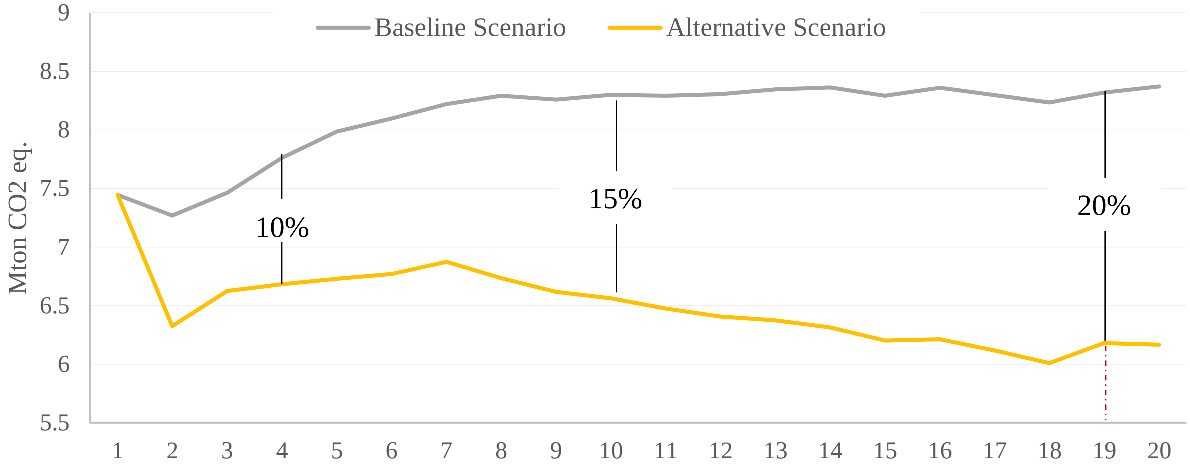


Figure 7.6. GHG emissions comparison under policy implementation

Throughout the time horizon, it is necessary to expand the capacity to develop more sustainable activities. It implies the use of resources, which is reflected in the difference in costs between the scenarios. In years 6 and 7, this difference reaches its highest point of 10%. However, this behavior is compensated with lower investments in other periods, which allows reaching a total accumulated cost at the end of the 20 years not higher than 5% of the base scenario's total accumulated cost as presented in Figure *7.7*. The economic goal is achieved from period 18, same way as the rest of the objectives, the model ensures its fulfillment for future periods.

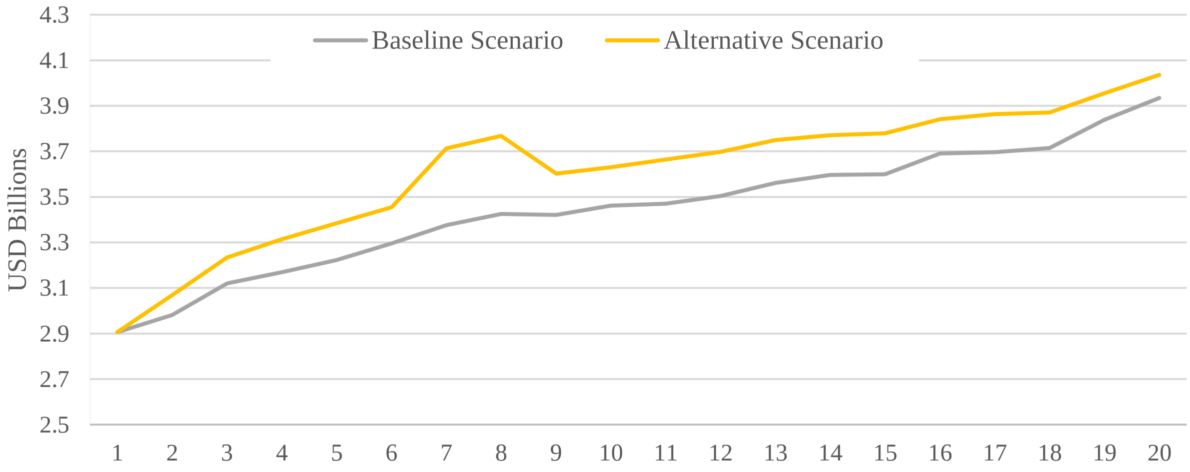


Figure 7.7. Cumulative cost comparison between scenarios

Considering the sources of GHG emissions, the reduction is particularly concentrated at the production stage. The use of electric vehicles contributes to small reductions of GHG emissions, from transportation activities. During the first five years an accelerated reduction in emissions from the transport sector is shown. Then subsequent changes in the network structure, end up reducing the impact of the fleet electrification. As a result, the total number of emissions from transport activities in the chain decreases by around 4% over the emissions of the baseline scenario as is shown in Figure *7.8*, despite the consistent growth in the number of electric vehicles.

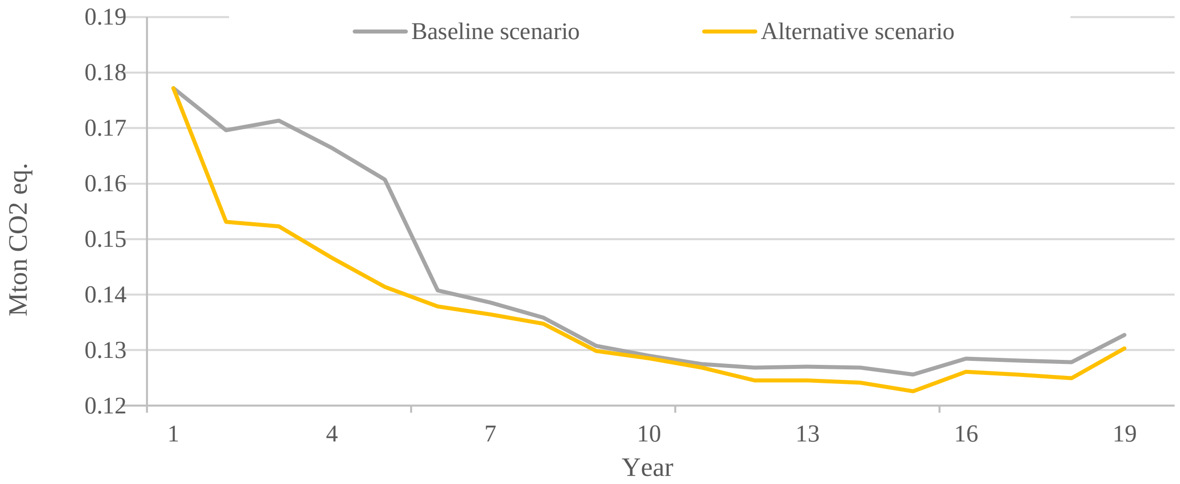


Figure 7.8. GHG Comparison in emissions from transport activities between baseline and alternative scenarios

In this regard, most reductions in GHG emissions at the sector level comes from the re-allocation of production zones and the development of silvopastoral systems at regions with highest production potentials. In this sense it promotes the development of production – processing clusters across the country as shown in Figure *7.9*

Notably, the central region of the country supports the largest production, mainly by high level productivity in regions such as Antioquia (1), Cundinamarca (2) and Boyacá (4). Moreover, the figure shows the high processing capacity at Cundinamarca and Antioquia, followed by Boyacá and Nariño. The results is explained by the highest centralization of the country. For instance, around 20% of the total population of the country is concentrated in Cundinamarca. For other regions located in the north or in the south the results show the favorability of inner production – processing like in Cesar (6), Magdalena (7) y Nariño (3).This reflects the importance of network structure and policy development in the fulfillment of environmental and social compromises. The following section shown the evolution of conventional and silvopastoral systems at different regions over the time horizon.

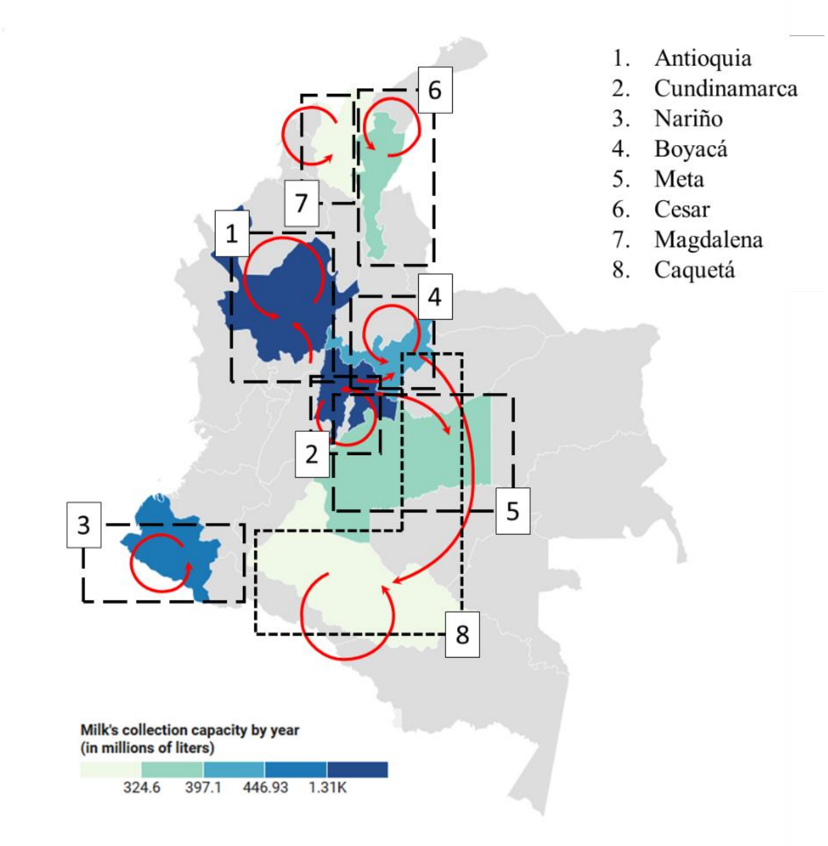


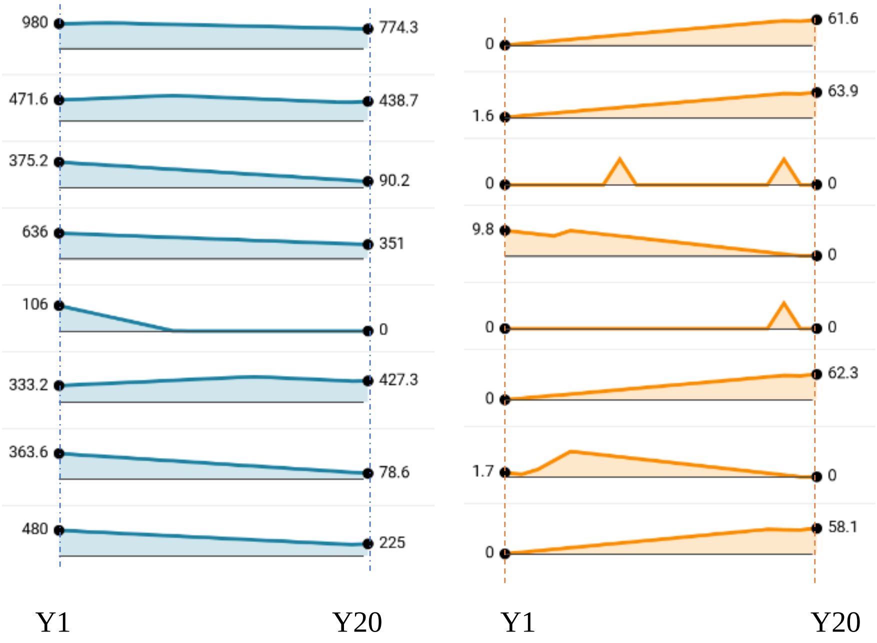
Figure 7.9. Production - Processing regional clusters

3.6. Re-allocation of capacities

Table 7.9 summarizes the changes in production capacity that occurs in the alternative scenario for every region. In this case, the total area occupied for extensive pastures goes near to 64% of the initial capacity, from 3,745,600 to 2,385,190 ha. Simultaneously, silvopastoral systems present a substantial expansion over the time horizon, mainly in the regions specializing in milk production. The total number of hectares transformed to silvopastoral systems adds up to 245,890 ha, representing 9% of the total area used by the year 20.

It is worth pointing out how the total area occupied remains practically unchanged in the tropical highlands. Indeed, Cundinamarca, central region of the country, increases its capacity around 50%. In contrast, the occupied land reduces considerably in the low tropical lands, until the disappearance of milk production activity in Córdoba. This situation shows how the productive transformation of the sector leaves farmers with low levels of productivity behind. Hence, the production is mainly centered on the highlands, here soil conditions, road infrastructure and closeness to the greatest consumption points constitute a trigger for the development of the industry.

Table 7.9. Production capacity changes in the alternative scenario



Region	Conventional		Silvopastoral systems		Farm type
Antioquia	980	774.3	0	61.6	Dairy
Boyacá	471.6	438.7	1.6	63.9	Dairy
Caquetá	375.2	90.2	0	0	Dual purpose
Cesar	636	351	9.8	0	Dual purpose
Córdoba	106	0	0	0	Dual purpose
Cundinamarca	333.2	427.3	0	62.3	Dairy
Magdalena	363.6	78.6	1.7	0	Dual purpose
Nariño	480	225	0	58.1	Dairy
	Y1	Y20	Y1	Y20	

Additionally, at the end of the time horizon, the total occupied area sums up 2,631,080 ha, representing the release of more than 30% of the initial use of land. During near the first decade, as an effect of the higher animal load per area and the increase in productivity per animal, the alternative scenario presents a constant and smoothly release of land, this behavior gets more intense from year 13 and onwards, finally the land use objective is achieved after 19 periods. Figure 7.10 presents the yearly use of land for both baseline and alternative scenarios.

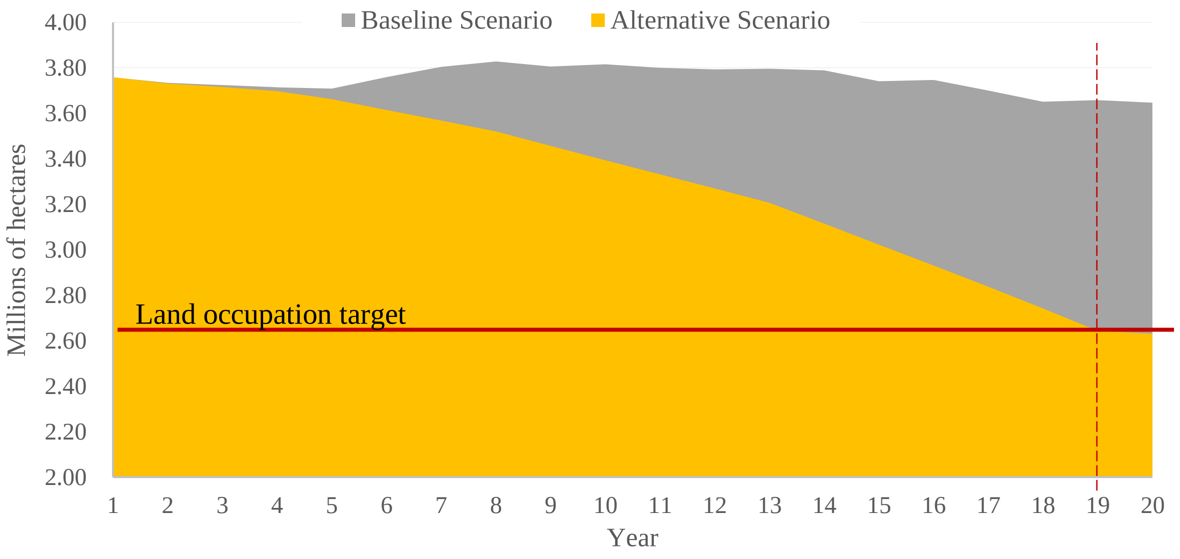
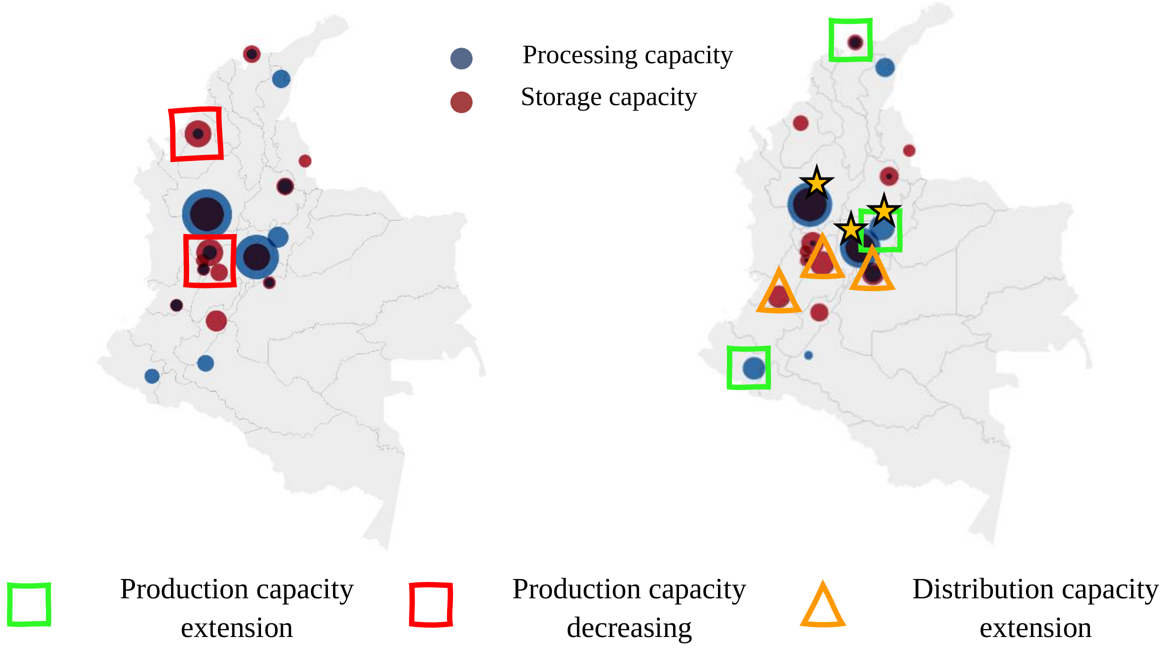


Figure 7.10. Use of land according to baseline and alternative scenarios

Figure *7.11* presents the new allocation of processing and storage capacities in the alternative scenario at the end of the 20 years. The processing capacity grows about 33%, with the most significant changes in Boyacá, Meta and Nariño, where the capacity goes further twofold (*green squares in b*). Besides, processing capacity reduces significantly in Cesar, Santander, and Valle del Cauca. In these regions, the final processing capacity is about only 20% of their initial capacity. About 75% of the processing capacity is installed in the central zone of the country in the regions of Cundinamarca, Antioquia, and Boyacá (*yellow stars in b*), close to the most relevant milk production zones in this scenario and the populated cities in the country. Concerning the storage capacity, it increases by about 35% to the end of the time horizon. Storage capacity threefold at Meta, Tolima and Valle del Cauca (*orange triangles in b*). Meanwhile, it reduces considerably at Córdoba, Quindío, and Risaralda (*red squares in* Figure *7.11a*).



(a) Year 1 *(b)* Year 20

Figure 7.11. Production and storage capacity in the alternative scenario

The re-organization of the supply chain bring within it some labor market dynamics. On the one hand, the expansion of the sector and the reduction of informality in the industry, promote the creation of new job opportunities in manufacturing and distribution process. On the other hand, reduction of occupied land and promotion of silvopastoral systems cause the loss of certain number of employees at rural areas, mainly in dual-purpose farms. However, it is not fair neither desirable to compensate agricultural and industrial job opportunities since the skills required to go execute one or the other are not equiparable. Hence, to avoid adopting a compensate mentality by bypassing the differences between agricultural and industrial job offers a separated analysis of employment in the supply chain is presenting in the next section.

3.7. Employment in the alternative scenario

In the alternative scenario, the generation of employment at processing and storage tiers remains unchangeable regarding the baseline scenario. At these stages, employment generation results from the industry's efforts to expand the coverage of demand by including new smallholders in the formal sector. On the other hand, there are differences in the number of layoffs at the production tier, between baseline and alternative scenarios, because of the capacity to transform lands. Figure *7.12* presents the number of lost jobs in farming activities over the time horizon for baseline and alternative scenarios.

Because of a higher capacity for land conversion to silvopastoral systems and enhance productivity, the alternative scenario presents a larger layoff rate in the agricultural sector during the first years of the planning horizon. In period 7, for both scenarios, the number of new employees created in silvopastoral activities matches the number of employees lost in conventional farming, which means the number of employees at this point is equal to the initial number of employees in period 0. From this point on, there is an increasing loss of jobs in the sector due to reduced land for milk production. Finally, in period 19, the employment goal is reached.

As stated before, the model ensures that the alternative scenario does not incur greater layoffs than the baseline scenario during the planning horizon. Nevertheless, this output forces the relocation of nearly forty thousand agricultural jobs. It implies the training of workers in new agricultural activities and the specialization of activity in the farms. For instance, dual-purpose farms with low milk production rates, might concentrate efforts in increasing meat production. The result is related with release of land explained in the previous section. The reduction of productive units is a common output of productive transformation process in the dairy industry as is noted in (Cadena et al., 2019).

The model estimates the number of lost jobs per region, which is a valuable source of information for the development of economic land use policies, and it is useful as well to the construction of regional development plans. For instance, it might be useful for establishing growth boundaries for the development of the milk production activity or production quotas per region. Correspondingly, it reveals that to construct a competitive agricultural sector, the agricultural development plan must be aligned with land productive capacities by regions.

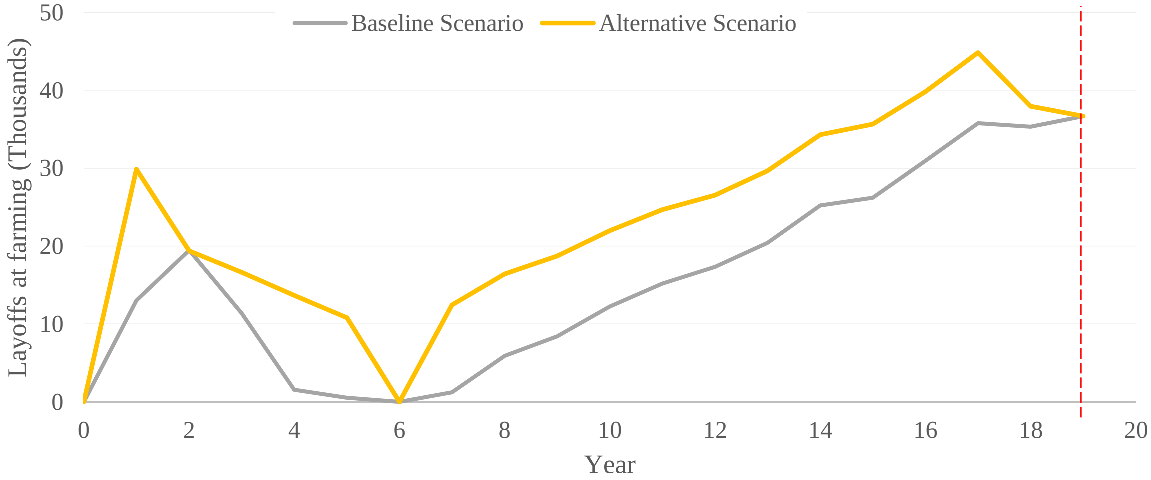


Figure 7.12. Employment in farming activities

3.8. Transportation activities in the alternative scenario

Currently the use of electric vehicles in the network is in a primary phase, although is in the plans of the main actors in the industry, and there are tax benefits to their acquisition, the capacity is still reduced and their growth does not seem to have an acceleration in the short term. Figure *7.13* shows the increase in the quantity of dairy products transported using electric vehicles from distribution centers to demand points. Although there is a constant growth in the capacity, the current number of vehicles that can be incorporated into the sector is still too low to make a significant impact on the entire sector, as presented in Figure 7.8. Indeed, these about seventy millions of liters of milk transported by electric fleet per year does not represent more than near to 1.3% of the total amount of products sent to consumption regions.

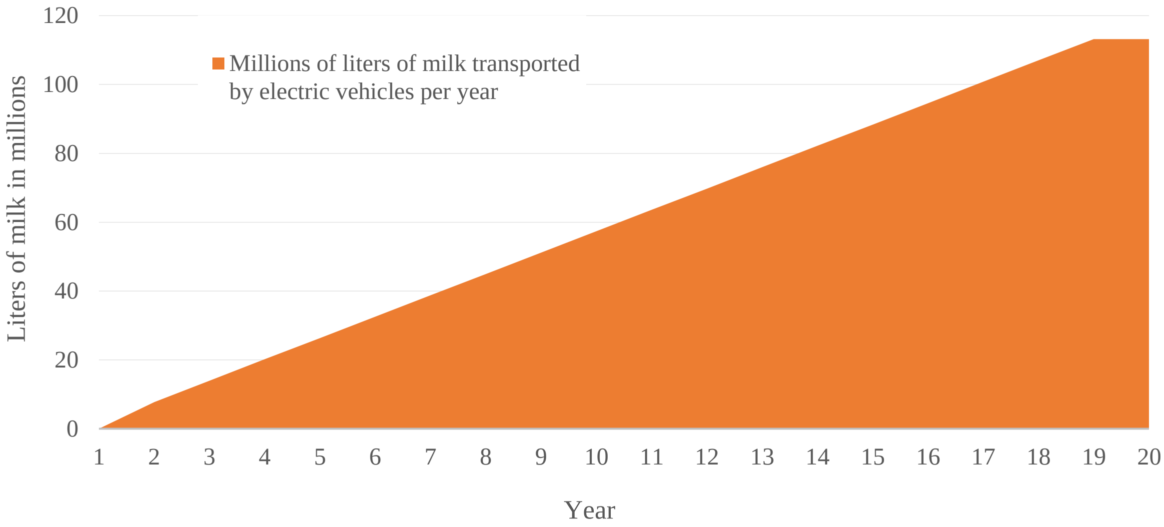


Figure 7.13. Electric fleet capacity in the alternative scenario

4. Analysis of the results

The current section provides an overview of the results of the optimization approach. Figure *7.14* is a graphic representation of the behavior of the optimization approach in the alternative scenario, here, red slots represent periods in which the goal is not met, and on the contrary whether the goal is reached it is represented with a green slot. The graph shows how all the key sustainability indicators manage to achieve the proposed objective at the beginning of year nineteen, and the model ensures compliance in onwards periods.

Figure 7.14. Time to sustainability graphic summary

Criteria for cost and land occupation get within acceptable values in year 18, while target for GHG emissions and employees are achieved in year 19. The results show the advantages of policy implementation in the promotion of silvopastoral systems. Advantages on its promotion are appreciated in the long term, however, it is important to develop financial mechanisms for supporting involved farmers. In the final configuration of the sector about a million of hectares are released for other agricultural uses. However, this situation also causes the destruction of about forty thousand employees in the agricultural sector. Hence, the promotion of friendly environmental policies must work along with the implementation of social policies, aiming to create regional capabilities for reallocating workforce in croplands or forestry activities.

One of the most interesting results is the displacement of productive capacities to highlands regions. These regions are characterized by higher population density and high cost of land. However, according to the results the creation of production and processing clusters is a relevant issue for the integral development of the sector. The central region of the country which host near 40% of the total population also hosts 75% of the milk processing activity and 37% of milk production lands. Possible conflict land uses are ahead since high quality soils are utilized in the region to the construction of residential units to accommodate the growing population in the center of the country. These results evidence the need for promotion of decentralized activities and the encouragement industry development in distant regions. Moreover, it reflects the importance on the development of road infrastructure to access markets in reaching sustainability goals.

At the company level, results at useful to define promising regions for the installation or expansion of processing activities, according to the development of the sector.

5. Sensitivity analysis

On the evaluation of policy implementation one of the most relevant issues, is the consideration of uncertainty in the development of the policy as well as in the outcomes of the implementation. The data used to evaluate the application of policy might be subject to certain inaccuracies, either by the source of the data or the extrapolation to different context situations. Although, every assumption has been made following the principles of relevance, transparency, completeness, consistency, accuracy and conservativeness, the standard action protocol to the evaluation of policies suggests an uncertainty analysis in these cases (WRI & WBCSD, 2014). The current section presents a sensitivity analysis of some of the main factors affecting the outcomes of the implementation of silvopastoral systems in the dairy industry in Colombia. Sensitivity analysis assesses the contributions of the inputs to the total uncertainty in analysis outcomes.

5.1. Level of adoption

Implementation of silvopastoral systems in dairy and dual-purpose farms is associated with enhanced productivity, increasing in animal load, and growth in farmer´s incomes. As reported by (Tapasco et al., 2019), silvopastoral systems promotion is one of the initiatives meeting the conditions to go for a scaling up to help the sector facing mitigation and adaptation to climate change. Moreover, it is recognized as an institutional initiative and component of the policy of the agricultural sector transformation. However, as mentioned by Tapasco et al. (2019), there is no plan designed to its large-scale promotion. Indeed, scaling-up potential of silvopastoral systems has been topic of interest since its early implementation (Calle et al., 2013). In this regard, national and regional capabilities to the development of silvopastoral systems remaining uncertain. Largely due to the high initial investment and knowledge required for the implementation of these grazing systems (Montagnini et al., 2013). Therefore, and analysis on different values to transformation capabilities might be useful to understand the impact of this parameter in the outcomes of the policy.

The current short scale projects in the country have reached on average a transformation rate over five thousand hectares per year as evaluated in baseline scenario. As parameter uncertainty cannot be determined, it is not possible to represent it through a probability distribution, instead of that the current approach considers different adoption level rates during the horizon planning. It considers, for instance, large-scale appropriation values in ranges fivefold, sevenfold, tenfold and fifteenfold respect to the baseline scenario. Table 7.10 presents the impact on the timeframe until meeting of sustainability goals considering different yearly transformation rates to silvopastoral systems. From the results it is possible to observe that larger transformation capabilities are associated with quicker return investment since the timeframe costs reduce as the transformation capability increase. For instance, considering a transformation rate of 28,000 ha/year the economic objective gets under control in year 18, at incrementing the transformation rate to 40,000 the period goes down to 15.

Likely, the larger the adoption level, the shorter the period to meet environmental goals. As expected, because of enhanced productivity rate at implementing silvopastoral systems, releasing of land to other agricultural activities occurs within a shorter period. GHG emissions objectives are met sooner.However, the reduction finds a boundary since the model includes also a maximum level to the reduction of lands in conventional production systems.

Finally, at scaling-up silvopastoral systems, the social dimension is less affected, becoming the limiting factor in achieving sustainability over the time horizon.

Table 7.10. Timeframe in years to meet sustainability objectives

		Sustainability goals			
Scenario	**Hectares**	**Costs**	**GHG emissions**	**Land**	**Employees**
Alternative	+ 28000 ha/year	18	19	18	19
B	+ 40000 ha/year	15	17	18	18
C	+ 60000 ha/year	14	16	17	17
D	+ 80000 ha/year	9	16	15	17

Large scale appropriation influences the time to reach sustainable goals in the sector. However, the path to reach sustainability goals in the sector goes beyond fifteen years in any case. Then is important to evaluate how to manage financial resources to its promotion. Higher appropriation rates could lead to higher investments during the first periods, however, considering a joint action in the three dimensions, it does not represent and considerable speed up for environmental and social conditions. In this regard, the transformation rate should consider the inner conditions of the sector along with the development of the industry carried out by processing companies, trough the promotion of clusters and the assurance of supply for existent and new competitors. In other words, there is no need to rush pushing unnecessary pression on the sector but to consider the harmonious reach of goals, which necessarily included in a holistic view of the sector and region.

5.2. Policy effectiveness

A second condition worthy to consider is related with the performance of the policy implementation. From an economic point of view, silvopastoral systems are associated with higher farm revenues due to improve cattle productivity (Montagnini et al., 2013). From an environmental point of view, silvopastoral systems offer improve erosion control, watershed protection, biodiversity enhancement, and larger carbon sequestration when compared with conventional grazing lands (Braun et al., 2016). At analyzing social impacts in terms of employees, combination of forestry and cattle activities might provide larger jobs opportunities. Previous studies analyzing the role of silvopastoral systems at reaching sustainable goals, have revealed differences in the outcomes regarding cattle productivity. For instance Solorio et al. (2016) state milk production might go up twofold per hectare when compared with conventional production systems. Chará et al. (2017), found a wide range of improvement going from 70% up to 300% after a 9-year evaluation of substitution of conventional milk production to silvopastoral systems. As mention by Reyes et al. (2017), not all the farms have the same baseline situation in terms of forage and animal production. Some farms, especially dairy specialized farms, might have starting point with high productivity mainly due to intensive use of chemical fertilizers while other farms have a very low production due to an extensive use of grasslands.

Considering the conditions of the case study, where the sector is mainly composed by smallholders, with low business investment and low technological development, improvements through silvopastoral systems implementation could cause a higher improvement that the one which was conservatively considered in the alternative scenario. Figure 7.2b. shows the estimated production improvement during the horizon planning when silvopastoral systems are implemented in relation with the trending improvement of conventional husbandry. In this regard, the assumed production enhancement is expected to be a high source of uncertainty in the assessment. As a result, scenario uncertainty is included to evaluate the impacts derived from different outcomes level of the policy. Although, some limits are known data is scarce to construct a probability distribution. The analysis made assumptions about the production efficiency improvements derive from the implementation of silvopastoral systems based on yielded results in previous studies. Table *7.11* presents the assumed values for productivity improvement over the assessment period.

Table 7.11. Estimated values for productivity improvement in a 20-year horizon time between silvopastoral systems and conventional systems

	Alternative scenario 1	Alternative scenario 2	Alternative scenario 3
Productivity improvement	+70%	+100%	+150%

Table *7.12* shows the sensitivity of the overall results to the variation in each key indicator representing sustainability dimensions. The results indicates that the model is not highly sensitive to assumption about efficiency improvements. Considering higher productivity rates in alternative scenario 2 and 3 derives in only minor reductions on total cumulative cost and GHG emissions. Because of the condition of the model, the goal of total release land is met, and the difference in the minimum required time to reach all of the sustainable goals, is reduced only in one year in alternative scenario 3. On the other hand, the number of agricultural jobs reduce as the productivity rate increases. Alternative scenarios 2 and 3 have increased in the number of jobs lost associated with milk production, 4% and 11%, respectively in comparison with Alternative scenario 1.

Table 7.12. Sensitivity analysis for ex ante scenarios

KPI	Alternative scenario 1	Alternative scenario 2	Alternative scenario 3
Total cumulative cost (*USD Billions*)	72.43	72.18	72.26
Total cumulative GHG emissions (*Mton CO2 eq.*)	129.55	129.33	128.94
Total release land (*thousand hectares*)	2631.07	2615.08	2631.07
Layoffs (*thousand employees)*	29.4	30.6	32.6
Time to sustainability (*Years*)	19	19	18

These results reveal the importance of the chain structure on meeting sustainability objectives. The reallocation of production zones and the construction of production-processing regional clusters result vital to sustainability objectives compliance. In addition, the results stress the importance of land use according to its productive potential. The development of production capacity at specialized dairy regions is a consistent outcome.

6. Conclusions

This chapter presents the performance of the ex-ante sustainability assessment model to the design of a supply chain network in the dairy industry. A specific case of the Colombian dairy industry has been evaluated. The model uses real data coming from national agencies, sector unions, milk industry's stakeholders to stablish a baseline scenario and to stablish trending conditions to the evaluation of the future development of the sector. The model contrasts, in a multi-period approach, the evolution of the sector when the decisions are guided solely by economic interests and its evolution under environmental policies and national commitments for sustainable development. Based on the sustainable development objectives and national sustainable development commitments, the model establishes desirable target values for the multiple key indicators addressing sustainability identified in Chapter 5.

In the first step the model evaluates the performance of the sector regarding economic criteria. Results for cost structure are in the range of previous analyses considering cost drivers in the dairy industry. It let us in partial extent to validate the results and trust the outcomes of the model. The model yields values for GHG emissions, land use, employment generation and cost for a twenty-year time horizon, while consider trending evolution on milk productivity and ensure informality reduction in the market.

In the second step, the model considers the implementation of an action policy, and calculates the required time to reach the targets in the three dimensions of sustainability as the structure of the supply chain network is modified. The results show the relevance of considering production tier in agri-food supply chains in social and environmental factors. It reaffirms the need for a holistic view of the supply chain when assessing sustainability. Moreover, it shows the relevance of policy application at encompassing efforts to reach sustainable development. Particularly, it shows how the impact on GHG emissions of electric fleet usage for distribution activities might be limited and insufficient to reach accountable results. Meanwhile, support to production activities and the creation of production-processing clusters might represent advantages for the sector.

A sensitivity analysis has been developed to evaluate how different factors related with action and policies application, could have impact in the results. Specifically, we consider, first, policy adoption level that refers to the investment scale for action development, and second, policy effectiveness that allude to the expected improvement of policy application. The results show that sustainable development for the dairy industry in Colombia is a long-term effort, which requires the implementation of joint actions at the national and regional level.

Chapter 8 Conclusions and future research

This thesis addresses the problem of designing a supply chain network when considering social, environmental, and economic factors. To deal with the problem different modeling approaches are proposed during the development of the project. Indeed, this thesis explores single-objective and multi-objectives modelling approaches, using, individual and composite indicators to represent sustainability criteria at the supply chain level and discuss their applications, opportunities, and shortcomings. Unlike other studies on the matter, which focus mainly on developing computational efficient algorithms, this work is additionally centered on the discussion of sustainability and the link between supply chain management and sustainability assessment. In particular this work is specially interested in the evaluation of sustainability in strategical decisions in the supply chain under policy application.

Recognizing the link between sustainable development and sustainability assessment, this thesis starts by presenting a review on the supply chain network design problem, with an intentional interest in compiling the metrics included in the problem to address with economic, environmental, and social criteria. The work was mainly focused on the evaluation of the indicators used in real application of the network design problem. The review presents the most common criteria used to represent different categories in the three dimensions of sustainability. Briefly, it identifies financial performance being the most predominant category in supply chain management at assessing sustainability at economic level, air pollution in the environmental dimension, and in social dimension, the most influential categories are working conditions and social development.

Besides, the studies were classified according to sector of application and country of origin of the case study. It shows how manufacturing sector has received great attention mainly in Europe and Asian countries. Other sectors, particularly the agricultural sector have been neglected, despite of the relevant interactions of social, environmental and economy factors that converge there. In this regard, the review discusses opportunities to the evaluation of sustainability in other sectors, to explore cases in Latin American countries and to adopt and to define sustainability criteria in relation to the specific greatest challenges faced by every industry. In this sense the proposition is instead of developing generic models to assess sustainability, turn towards the proposition of custom model that address with the real sustainability factor in the industry.

This work considers the assessment of sustainability at supply chain level from two different perspectives. In the one hand, it considers a corporate sustainability view at supply planning optimization. In Chapter 3, we present a dimension-driven approach, a MILP for the design of a generic supply chain network. The model is solved considering three different objectives, one for each dimension of sustainability. The results show the effect of the decision criteria on the supply chain structure. It is useful to recognize the capacity of improvement in the supply chain by computing ideal values to every dimension considered. Moreover, it exposes the impossibility of reach them all at once due to the conflicting nature of the objectives. Chapter 4 presents, a multi-objective approach to deal with the synchronic inclusion of sustainability criteria. We discuss the different multi-objective approaches in the related academic literature and their ways to deal with decision-maker preferences. Besides, it discusses some shortcomings related to the disregard of setting goals for every dimension at assessing sustainability. The model is solved using a Chebyshev goal programming approach. The *non-preference* solution's approach led to a feasible solution without establishing biased preferences on the objectives. But, more important, it opens the discussion about targets and time horizon considering sustainable development in supply chains.

On the other hand, this work addresses sustainability in a wide-industry perspective. This work discusses the need of holistic view at addressing sustainability in long-term decisions at supply chain level, since the separated and individual efforts from companies might not cause the reduction of emissions that is required to achieve national and global commitments to climate change and sustainable development. Therefore, this work contributes to the definition of an ex-ante sustainability assessment model to the design of the supply network in the dairy sector in Colombia presented in Chapter 6. The multi-period model deals with the mega-location of production, processing, and distribution facilities to meet a set of sustainability objectives under the application of policies and actions. Unlike previous works adopting a trade-off mentality on economic, environmental, and social performance, the model aims to meet defined target for the defined key indicators in each dimension of sustainability, as modifying the structure of the supply chain over a time horizon. As a novel modeling aspect, the evaluation includes the use of land for agricultural activities and their transformation into sustainable practices.

The model examines different scenarios, considering variability for relevant parameters on the policy execution, and their outcomes were compared. The results in Chapter 7 shown the relevance of creating production-processing clusters taking advantage of the potential land use. Besides, the results shown the loss of productive units and jobs in the sector because of the productive transformation. These results are consistent with productive transformations of agricultural sector in other countries (Cadena et al., 2019). The model may give insights for policymakers as it shows the need for supportive economic, social, and environmental policies to the fulfillment of sustainability objectives. Public administration plays a fundamental role in promoting innovation and sustainability among enterprises. It is also in charge of facilitating capital access, regional capabilities construction and the definition of lever and incentives as encouraging voluntary behavior change (Paletta et al., 2021). It also results useful for companies to support strategic decisions since it may identify promising supplier regions, define the organization of production-processing clusters, and point out the main drivers for sustainability in the sector.

Considering the relevance of understanding the industry at assessing sustainability, this work dedicates a separated section to present an overview of the dairy industry in Colombia. It discusses the relevance of the sector considering national greenhouse gas inventory and social conditions. It discusses the importance of considering stakeholder's sustainability definition to identify key indicators criteria in the three dimensions of sustainability. Hence, although there exists common factor to assess sustainability at supply chain level, it is important to verify, the relevance of these factors in the context of the industry. At least two reasons might be mentioned in this regard. First, the availability of data, to measure and control the proposed key indicator. Second, the relation between the factor and the current challenges of the sector to move towards sustainable development.

As a part of the description of the case study, we present a brief of the planned mitigation and adaptation policies and actions in the agricultural sector and the relation with environmental and social factors. By considering the most related and promising action to be implemented in the sector, we evaluate future scenarios to the productive transformation of the sector. The results show the inherence of policy in sector development and its major role in the promotion of sustainable development paths. It shows as well that sustainable development for the dairy industry in Colombia is a long-term effort, which requires the implementation of joint actions at the national and regional level.

This work contributes to the discussion on sustainability assessment and the need of establishing sustainability goals at addressing supply chain management decisions, here particularly, in supply chain design. As stated by (Pope et al., 2004) assessing sustainability requires a well-defined concept of sustainability. Efforts might fall short at presenting alternative solutions when targets are not defined. In this regard, this work highlights the relevance of assessing improvements within a context in which desired targets or goals are discussed. Moreover, it examines the definition of sustainability key performance indicators consequently with what sustainability means for the stakeholders in the specific case of study here presented.

It also presents a set of key indicator performance to assess sustainability in the agrifood sector, specifically in the dairy industry in the long-term. Decisions at the strategical level of supply chain, might define tracks for improvements and actions at tactical and operational level. In this sense, decisions in the long-term play a significant role at limiting improvement potential of decisions in a shorter action period. The performance of the ex-assessment sustainability assessment model is tested on a case study in Colombia, a developing economy, with realistic data coming from trade unions and public entities in the country. Few works have considered a wide-industry perspective to the evaluation of sustainability in the design of supply chains and in the best of our knowledge, no work have presented an ex-ante sustainability model to the evaluation of policies in the long-term and its impacts on industry structure.

Additionally, on the basis of the work developed in this thesis, some ways for further research are suggested below. First, it focuses in the definition of key performance indicators for assessing sustainability in the context of the case under study. In this regard, more attention should be given to the accurate definition of sustainability criteria at evaluating strategical decisions in the supply chain context. Definition of metrics and measurement methods must foster an interdisciplinary approach which includes future views or prospective analysis from local authorities, trade unions, public administration, scientific counselors and managers, closing the gap between ecology and supply chain management field at addressing sustainability (Blass & Corbett, 2018). A proper definition of sustainability will allow for an appropriate selection of sustainability measurement criteria. This provides guidance to bring supply chain participants and outsider institutions together towards a common goal and minimizes the risk of greenwashing.

There is a void to fill regarding the development of social aspects at addressing long-term decisions in supply chain management. Although quantifying social aspects is a complex and challenging task. The definition of indicators based on social indexes and the association of them to SDG’s offer the opportunity of establishing a framework and a goal for those criteria. However, it is important to stablish clear and measurable implications between supply chain management decisions and social aspects. Although, this effect uses to be clearer in operational and tactical decisions, such as, labor gender equity, fair payment rates or health conditions, among others. This relation often vanishes or blurs at evaluating long-term decisions. For instance, economy development by industrialization is not straightforward a solution for poverty reduction. Economy growth may or may not come together with growth on inequality during the development process depending on national characteristics, including how growth is achieved and mainly the policies to achieve it (Kniivila, 2002).

Regarding the modelling features, other realistic assumptions like imports and exports can be included into consideration. Globalization and free trade agreements represent a big challenge to meet environmental and social objectives. For instance, specialization and automation offer higher productivity rates in developing countries. Countries tend to produce commodities for which they have a comparative advantage offering low prices products in the existence of trade agreements. It might increase food footprint, and become a threat for local producers. In this regard, the model might deal with maximum quotas or taxes to analyze the behavior of the industry and serve as a support for policymakers.

Finally, uncertainty might be considered, regarding two elements. First, uncertainty as a characteristic of long-term decisions. It comprises parameters on the market, such as, supply, demand and costs. Despite accuracy on forecasting methods, decisions in the long-term are always subject to variability. Moreover, uncertainty could be associated to environmental assessment methodologies as it may or may not include some sources of GHG emissions (Sonnemann et al., 2003). In this sense, instead of establishing a unique value, it could be useful to consider an interval that with a certain level of confidence contains the actual contribution by unit of aggregation. Consideration of uncertainty may lead to more robust solutions. In this regard, solution approaches combining simulation and optimization techniques might be useful to deal with uncertainty at multiple parameters. To this aim input parameters are considered random but restricted by a known probability distribution for each parameter. Repeated executions permit the evaluation of multiple baseline scenarios and produce a distribution of output values, reflecting the combined uncertainty of multiple parameters.

Second, uncertainty on policy implementation and on policy efficiency. While the first case deals with parameter uncertainty, the second case deals with scenario uncertainty. In this case multiple methodological choices are available to implement. For instance, previous to the definition of action and policies, some pilots tests are carried out on a small scale, or expected results are calculated from the application of the same policy in an environment with similar conditions. However, results on implementation might variate for several factors including social and ecological conditions, and the construction of capacities to fund and construct the required capacities to support the development of the policy. Therefore, expected results coming from policy or action application might be different from the initially expected. Understanding uncertainty might provide useful insights to apply conservative assumptions.

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Appendixes

Appendix 1. Data source to the construction of the baseline scenario and projection to the case study

Parameter	Document	Source
Demand		
Apparent consumption	Consumption statistics 2019	Fedegan, 2019
Population growth	Departmental population projections by area	DANE, 2018
Production capacity	National agricultural survey	DANE, 2017
	Situational analysis of the dairy chain	MADR & UPRA, 2020
	Sustainable Colombian Livestock	Fedegan,
Processing capacity	National direct supplier of milk captured by the industry to the primary sector	UPS, 2020
Storage capacity	Web pages industrial partners	Alpina, Alquería, Colanta, Nutresa, Gloria, Parmalat
Production cost	Production costs statistics 2019	Fedegan, 2019
Processing and storage costs	Fluid milk processing costs: Current state and comparisons	(Dalton T. J., Criner G.K, Halloran J, 2002)
	Analysis of factors affecting production costs and profitability of milk and dairy products in Turkey	(Akin A. C, Cevger Y., 2019)
Capacity cost	Land costs	UPRA, 2020
	Analysis of factors affecting production costs and profitability of milk and dairy products in Turkey	(Akin A. C, Cevger Y., 2019)
Silvopastoral systems costs	Comprehensive analysis of intensive silvopastoral systems	(Montoya Reyes E., 2016)
	Silvopastoral systems and their contribution to improved resource use and sustainable development goals: Evidence from Latin America	(J Chará et al., 2019)
Production emissions	Life cycle assessment for the production of cattle milk in an intensive silvopastoral system and a conventional system in Colombia	(Rivera J., Chará J., Barahona R., 2016)
	Estimating of the carbon footprint in traditional and intensive silvopastoral systems for the production of milk in Colombia	(Rivera J., Chará J., Murgueitio E, Barahona R., 2015)
Processing emissions	Alpina sustainability report	Alpina, 2019
Transport emissions	Database of emission factors of Colombian fuels FECOC	(Arrieta A et. al., 2016)

Parameter	Document	Source
Employment	Annual manufacturing survey	DANE, 2018
	Structural analysis of strategi sectors: dairy sector	(Bohorquez N et al., 2012)
	Modal costs in Colombian Livestock	Fedegan, 2014
Land Availability	National agricultural frontier	UPRA, 2019
Land Productivity	Prospective 2039 dairy chain	MADR & UPRA, 2020

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AGRIFOOD SUPPLY CHAIN NETWORK DESIGN UNDER SUSTAINABLE DEVELOPMENT POLICIES

Specialty: Environmental Science and Engineering

Keywords: sustainable supply chain, supply chain network design, sustainable development policy, optimization, sustainability assessment, dairy supply chain

Abstract:

This work addresses the research problem of quantitative support for decision-making in sustainable supply chain network design (SSCND). We first identify the common key indicators utilized to assess sustainability in supply chain design applications. We propose both (*i*) a single-objective and (*ii*) a multi-objective modeling approaches to deal with environmental and social criteria to the design of a supply chain network from a company perspective. Considering a broader perspective of sustainability in supply chains, the unit of analysis is extended from a company perspective to consider a wide-industry perspective for the sector. We specifically consider the effects of policy application on encompassing the sector towards sustainable development and its impacts in the supply network structure.

The purpose of this work is to propose an efficient assessment procedure for the joint assessment of economic, environmental, and social performance for the design or redesign of supply chain network. A mathematical formulation considering the evolution of the supply chain and the construction of capacities in the long term is presented. To this regard, we define sustainability objectives according to the current conditions of the sector and the country. We compare the supply chain structure changes over a time horizon following an ex-ante sustainability assessment approach. Moreover, sustainability key performance indicators are chosen considering current sustainability challenges of the sector. The performance of the model is tested with an application in the dairy industry in a developing-economy country. It illustrates the utility of the model to evaluate national mitigation and adaptation activities in the design of supply chain networks. The need of setting targets when measuring sustainability in the supply chain field is highlighted. Results offer meaningful decision support to policymakers in evaluating implementation of policies and actions, and in the definition of strategical paths towards sustainability.

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CONCEPTION DE RESEAUX DE CHAINES LOGISTIQUE AGROALIMENTAIRES DANS LE CADRE DE POLITIQUES DE DEVELOPPEMENT DURABLE

Spécialité : Sciences et Génie de l’Environnement

Mots clefs : conception de réseaux de supply chains, politique de développement durable, supply chain durable, optimisation, évaluation de la durabilité, industrie laitière.

Résumé :

Cette thèse s’inscrit dans les recherches sur l'aide quantitative à la prise de décision dans la conception de réseaux de chaînes d'approvisionnement durables (SSCND). Dans un premier temp, nous identifions les indicateurs clés communs utilisés dans des publications scientifiques pour évaluer la durabilité dans les applications de conception de chaînes d'approvisionnement. Nous proposons ensuite (i) une approche de modélisation à objectif unique et (ii) une approche de modélisation multi-objectifs pour inclure les critères environnementaux et sociaux dans la conception d'un réseau de chaîne d'approvisionnement du point de vue de l'entreprise. En considérant la perspective plus large de la durabilité dans les chaînes d'approvisionnement, l'unité d'analyse est étendue d'une perspective d'entreprise pour considérer l’ensemble d’une filière au sein des différentes régions d’un pays donné. En particulier, nous étudions les effets de la mise en œuvre des politiques de développement durable sur la structure du réseau d’approvisionnement pour l’industrie laitière en Colombie.

L'objectif de ce travail est de proposer une procédure efficace d'évaluation conjointe des performances économiques, environnementales et sociales pour la conception ou la reconception d'un réseau de chaînes d'approvisionnement. Une formulation mathématique est présentée, qui tient compte de l'évolution de la chaîne d'approvisionnement et du renforcement des capacités à long terme. Nous proposons une approche d'évaluation ex ante de la durabilité pour comparer les changements dans la structure du réseau de la chaîne d'approvisionnement en vue d’atteindre les objectifs de durabilité. En outre, les indicateurs clés de performance en matière de durabilité sont choisis en tenant compte des défis actuels du secteur en matière de durabilité. La performance du modèle est testée avec une application dans l'industrie laitière d'un pays à économie en développement. Elle illustre l'utilité du modèle pour évaluer les activités nationales d'atténuation et d'adaptation dans la conception des réseaux de chaînes d'approvisionnement. La nécessité de fixer des objectifs pour mesurer la durabilité dans le domaine de la chaîne d'approvisionnement est soulignée. Les résultats offrent une aide à la décision significative aux décideurs politiques dans l'évaluation de la mise en œuvre des actions et la définition des voies stratégiques vers la durabilité.