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Green Supplier Selection in the Agro-Food Industry with Contract Farming: A Multi-Objective Optimization Approach

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Received: 31 October 2019; Accepted: 4 December 2019; Published: 9 December 2019

Abstract: An important contribution to the environmental impact of agro-food supply chains is related to the agricultural technology and practices used in the fields during raw material production. This problem can be framed from the point of view of the Focal Company (FC) as a raw material Green Supplier Selection Problem (GSSP). This paper describes an extension of the GSSP methodology that integrates life cycle assessment, environmental collaborations, and contract farming in order to gain social and environmental benefits. In this approach, risk and gains are shared by both parties, as well as information related to agricultural practices through which the FC can optimize global performance by deciding which suppliers to contract, capacity and which practices to use at each supplying field in order to optimize economic performance and environmental impact. The FC provides the knowledge and technology needed by the supplier to reach these objectives via a contract farming scheme. A case study is developed in order to illustrate and a step-by-step methodology is described. A multi-objective optimization strategy based on Genetic Algorithms linked to a MCDM approach to the solution selection step is proposed. Scenarios of optimization of the selection process are studied to demonstrate the potential improvement gains in performance.

Keywords: green supplier selection; contract farming; life cycle assessment; environmental collaboration; multi-objective optimization; agro-food supply chain

1. Introduction

Environmental awareness has shifted consumer behavior towards more efficient and environmentally-friendly products, including processed foods. This has led food manufacturers to find opportunities by developing strategies targeting eco-friendly consumers and markets, through the use of eco-labelling [1,2]. In order to satisfy these niche markets and continue developing this branding strategy, a shift from conventional food production to a more sustainable one has been progressively pursued. The transformation is that consumer awareness about the "greenness" of products is incentivizing a change towards alternative practices and technologies that may affect the entire agro-food supply chain (ASC).

One of the most important links in the ASC lies in the interface between farms and manufacturers, given that the raw materials needed to produce the current selection of food products at retail stores and markets are sourced. An important part of the environmental impact located at this point is due to agrochemical, water, land and energy use related to farming [3,4]. This is why there is an interest in both sustainable agricultural practices as well as green process design steps further downstream, in order to look at the sustainability of ASC, which leads to the potential improvements that could lie at the interface between farmers and manufacturers.

The study of this interface is sometimes referred to as the supplier selection problem (SSP). This subfield of supply chain management (SCM) has been tackled largely in the dedicated literature, where it is mostly described by taking into consideration a set of criteria, traditionally based on cost, delivery time and quality among many other components [5], to then classify and rank suppliers [6,7]. This paper looks at the SSP of an orange juice producing company that uses suppliers in a collaborative scheme, that additionally includes in their supplier roster, small and medium farmers, under a contract farming model. Furthermore, it proposes the use of the green supplier selection paradigm that incorporates environmental performance of suppliers in the selection process. The objective of this paper is then to show how with synergy made through collaboration, contract farming and a green supplier selection perspective, improvements in the performance of the food supply chain can be achieved in economic, social and environmental terms. It answers the specific research question: What is the result of including partnerships in a supplier selection decision modeling approach in terms of selection criteria within the green supply chain paradigm? This approach will be referred to in what follows as Partnership for Sustainability (PfS) (see Figure 1).

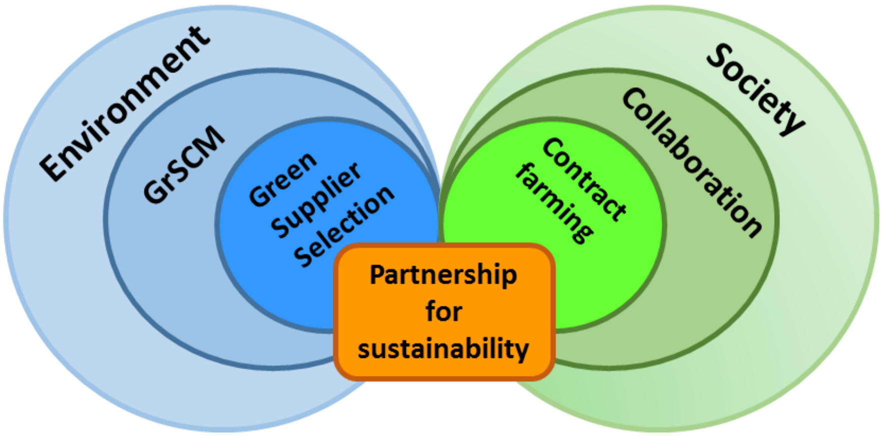

Figure 1. Partnership for sustainability method integration diagram.

In order to illustrate the approach and proposed solution methodology, a case study is developed focusing on the production and supplying of oranges produced in Mexico used for juice production. This case study is based on the locally available technological alternatives which are used at each supplying orchard, taking into account the local technological package and their corresponding production yields and related environmental impacts for the specific citrus fruit producing region. The methodological framework for the solution of this problem is based on the use of a multi-objective optimization strategy through genetic algorithms followed by a multi-criteria decision-making method in order to select a solution.

1.1. Green Supply Chain Management

The backdrop of the proposed approach lies in a promising and somewhat recent paradigm to evaluate and improve the environmental and overall performance of production systems called Green Supply Chain Management (GSCM). This approach integrates two conceptual scopes: Supply Chain Management (SCM) and Life Cycle Assessment (LCA). The former provides a framework to visualize and improve the economic and operational performance of productive systems by modelling the flow of materials, information and money, throughout the links in the production chain, with the end objective of economic profit [8]. The latter, is a technique to aid in the decision- making process by providing a system-oriented approach to evaluate the environmental impacts at some or all the stages in the life cycle of a product [9]. By integrating these two holistic approaches, the economic and operational objectives can be set side by side with sustainability objectives when trying to make decisions on design or improvements of the overall performance of a production system.

Although much progress has been made in the field, there are still opportunities in exploring the application of GSCM in different contexts [10,11]. This work proposes the extension of the current GSCM model to include special issues inherent in agro-food supply chain systems and by looking at the decision-making process of supplier selection in this context, i.e., when suppliers are farms.

1.2. GSCM Modelling and Optimization Approach

The modelling approach assumes that there is a set of products that can be differentiated by a "green" quality attribute based on the technological methods used to produce them. When a product is made with specific quality characteristics, for example "big" oranges, that have a higher demand and/or market price against, say, "small" oranges, this leads the orange farmer to change the production processes configuration and capacity (within physical and cost-benefit limitations), in order to increase the output of the most profitable product i.e., "big" oranges.

Let us consider that a new product quality attribute is now being associated with environmentally produced/processed products. These products are marketed through eco-labels such as: organic, bio, green, eco-friendly, etc. Let us also consider that these new attributes have changed the market value and pricing of the products, given that they are willing to pay more for the story behind the product and for precise information [12]. This type of labelling has been widely used since the 1990s in the U.S. and the 1980s in France [13]. It is interesting to explore the possible effect this could have when modelling and optimizing an ASC. Thus, the approach proposed here takes this green preference into account and integrates it within the current GSCM modelling and optimization methods.

In the literature, different methods have been proposed in order to solve these types of problems, some use MILP (Mixed Integer Linear Programming) [14,15] as a preferable technique for network configuration; others take into account non-linear behaviour that requires MINLP (Mixed Integer Non Linear Programming) capability [16], or a stochastic programming approach to handle uncertainties [17]. A relevant approach that has been widely used to handle the multiple objective nature of GSC models (sometimes in tandem with other modelling approaches such as MILP) is the so-called MOO (Multi-Objective Optimization) technique [14,18]; as well as other Multi-Criteria Decision Methods such as TOPSIS and AHP [19,20]. These final two approaches (i.e., MOO and TOPSIS) were selected to manage the complex decision-making that takes place when working with a SC scope. It may be important to point out that MOO through Genetic Algorithms was used instead of other approaches, such as Wighted-Formula and Lexicographic methods, given that it allows the modeler to take a black box approach, where objectives and constraints are not restricted in their structure [21]. The advantage of ease of use and adoption [22] allows for scalability and integration with other complex models with little or no modifications needed. This last point was critical in its selection due to its integration to a wider reaching green supply chain network design approach [23].

Our work assumes that production practices at all stages of the supply chain can be changed to improve environmental performance, which means the changes in consumer preference for "green" products have to be met by a market demand (as this attribute adds intangible value to the product). In supply chain modelling terms, using the orange juice production as an example, the following set of questions have been formulated:

- Production design problem: What agricultural practices should be used to add "green" value to the product at the raw material production stage e.g., optimal use of pesticides, fertilizers, gasoline powered machine, etc.?

- Product mix problem: What quantity of each quality-type orange should be produced to obtain the desired orange juice quality mix (e.g., "organic", "environmentally-friendly" or "30% less environmental impact")?
- Location-allocation problem: Which and how many orchards should produce environmentally-friendly oranges; which and how many should use intensive agricultural, in order to satisfy demand?
- Supplier selection problem: Which supplier to buy from? How much to buy? Which criteria to use to evaluate supplier performance?

In order to answer these questions, the Partnership for Sustainability approach takes the green supplier selection problem and integrates the benefits from contract farming and an environmental collaborative approach described in the following sections.

1.3. Green Supplier Selection Problem

In the field of supplier selection, there is a wide body of publications looking at many different aspects such as formulation, method and application [24]. These include recent works on green or sustainable supplier selection. Although Green Supplier Selection (GSS) has been named in different ways such as Green Vender, Green Purchasing, and Environmental Purchasing, most definitions coincide in its reach. We consider [25], and define Green Supplier Selection as "the set of purchasing policies held, actions taken and relationships formed in response to concerns associated with the natural environment." It goes on to clarify that "These concerns relate to the acquisition of raw materials, including supplier selection, evaluation and development." This integration is promoted because of the benefits that interaction of the different members of the supply chain produce, not only on sustainability issues, but also on economic and operations performance [26]. A review on Green Supplier Selection has highlighted some interesting research challenges [27]. According to these authors, the integration of Life Cycle Assessment (LCA) in the definition and measurement of environmental criteria offers an interesting methodological framework, since it involves a system-wide approach for environmental impact evaluation. Some other examples of GSS have been published for industries such as electronic and consumer goods [28,29]. A study on the effectiveness of a large-scale Sustainable Supplier program in Mexico was published. Among its conclusions, it suggests that a need to focus on micro and small businesses must be considered as an important objective in further research within the field [30].

This paper locates itself in these groups of research that support the use of LCA as a decision support tool for the supplier selection process and develops the case study in the context of an agro-food chain in order to contribute to the current body of research in the field. It also contributes to the potential improvement from contract farming and its derived environmental collaboration that is further discussed in the following section.

1.4. Contract Farming

In the SCM paradigm as in the GSCM, a central or focal company (FC), as proposed by Seuring and Muller [10], is characterized by being the designer or owner of the product or service offered, governing the supply chain, and having contact with all SC stakeholders including the customers. The FC can also sometimes be the processing or manufacturing company, as is the case of our case study.

We proposed that the FC be the integrator firm within the context of contract farming as described by Rehber [31], under a Management and Income Guaranteeing contract [32], also known as a Production Management Contract (PMC) [33]. They describe the PMC type of contract model as one that both specifies product quality measures that are acceptable to the integrator, and the integrator providing production resources, takes on substantial managerial responsibilities, and supervises the supply chain activities. This form matches well with the green supplier development aspect of the GSCM approach, given that green supplier development draws its importance from the fact that suppliers are often small and do not have the knowhow or resource necessaries to face the environmental issues related to their business process [10,34]. This is why some research has been focused on collaboration, certification and education of suppliers [35–37]. The similarity in the scope and roles that different elements play in GSCM and contract farming models are illustrated in Figure 2.

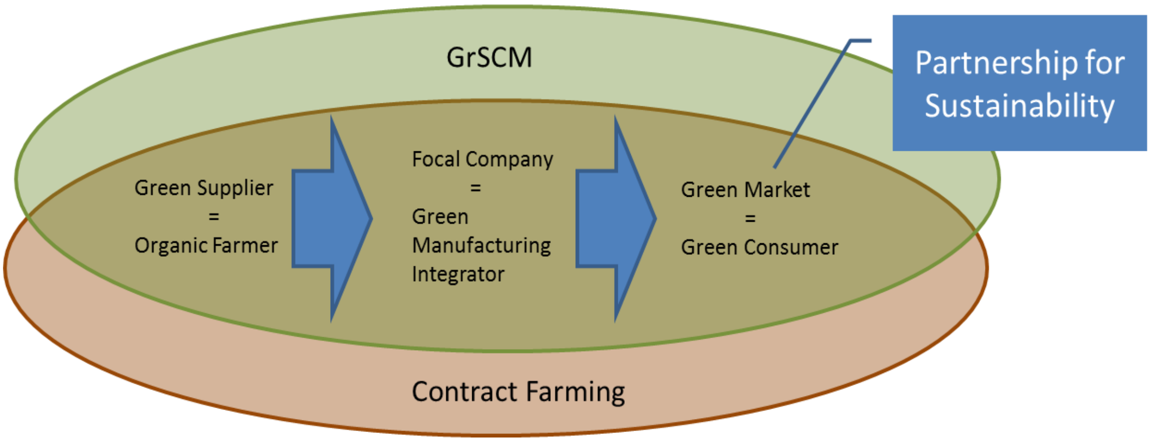

Figure 2. Analogy between Green Supply Chain Management (GSCM) and contract farming elements.

The manufacturer used in the case study is both the Focal Company and Integrator, thus the model we present is adapted to this type of supply chain configuration. In other words, this paper is limited to this situation, i.e., where the focal company is the processing company, and is the principal negotiator with suppliers and distributers or consuming markets.

It is important to note that the details related to the negotiation and contracting stages are out of the scope of this research; however, the contract form that allows for the collaboration and technology transfer, that includes which technological package to use at the suppliers' fields, is part of the general approach.

Contract farming as described in a special report for FAO by Eaton and Chepherd [38], and is the use of contracts to build a foundation of collaborations between the FC and the supplier, where the whole or a fraction of production output from suppliers is bought guaranteeing (not without risk) a reliable source of product, while the supplier has an assured buyer. According to the FAO report, this model is an effective way of taking advantage of the investment power and knowledge base of the FC by transferring technical skills in order to use the synergy reached to improve supplier performance. This, in turn, helps to guarantee both parties a partnership for growth and helps mitigate and spread risk. Most importantly, within the context of this paper, it allows the FC to require and share technological packages or practices to be used at the supplier field in order to obtain conforming and consistent raw materials. It also gives enough flexibility to find the optimal supplier technology package selection.

1.5. Partnership for Sustainability

Partnership for sustainability is derived from the premise documented by Vachon and Klassen [39], in a paper related to the improvement in operational performance based on partnerships in the supply chain. They use the term "green project partnership", to describe "the extent of interaction between a plant and its primary suppliers and major customers in developing and implanting pollution prevention technologies." This paradigm is considered here and implemented in what follows into the food supply chain within the GSCM scope. As pointed out by Vachon and Klassen [39] and corroborated by Albino et al. [40], the integration of suppliers through partnerships has a positive effect of operations performance, and furthermore may stimulate gains in integrated knowledge and knowhow from the supply network [41], which, in turn, can have a positive effect on the development of agricultural practices and supply chain negotiations and distribution issues.

This paper outlines a framework to apply this type of partnership as a step-by-step methodology, to distinguish from green project partnership as a general term that describes partnerships both with suppliers and customers. It will be referred to in the following as Partnership for Sustainability.

2. Materials and Methods

The general approach to solve the SSP consists of implementing a set of steps, where after scouting a list of potential suppliers, a discrimination process is made through basic common sense judgements; this is followed by a measurement and characterization step based on requirements and desirable attributes. Then, a classification or ranking is done in order to target negotiations and contracting (Table 1).

Although this can be a dynamic process, meaning that there are new suppliers being added and old suppliers eliminated from the approved supplier catalogue, it can also be part of the strategic and tactical planning stages for long-term improvements that can be reviewed periodically. This research is situated in the latter approach.

The steps in Table 1 extend from the conventional supplier selection process to form part of a holistic approach to characterize the potential partners in addition to modelling, optimization and selection steps, to end with the execution of a contractual negotiation and agreement. This last step is not yet described in detail since it falls outside of the scope of this paper; steps 3 to 6 are described in detail in this section.

Table 1. Partnership for Sustainability Supplier Selection processes.

No.	Description
1	Pre-selection or scouting of suppliers
2	Short listing based on common sense judgment
3	Supplier characterization
4	Supplier network model
5	Supplier network optimization
6	Supplier network selection
7	Supplier negotiation and contracting

2.1. Partner for Sustainability: Supplier Characterization

The current SSP is framed by looking at a set of characteristics required by the production plant being supplied. The most common characteristics evaluated include quality, cost and delivery performance; although some efforts have been made to include environmental criteria in the supplier selection process, this kind of approach gaining traction in becoming the norm.

It must be also highlighted that the evaluation methods found in the domain literature describe the supplier selection process as a search for the most competitive vender without looking necessarily at the potential benefit of a long-term partnership, although there are some instances. In this approach, the characterization process itself consists of looking at the requirements or criteria most valued by the FC and implementing scoring or measurement systems in order to allocate a value to each supplier based on observed or estimated performance. For this purpose, the Partnership for Sustainability takes the potential capability of the supplier given the field or region characteristics (i.e., land and environment), and the technological package that can be used into account. This means that the question is not only which supplier to choose but also what technology should be matched to obtain the best criteria measurements.

The justification of this approach is also made given that many of the sustainability leaders, at least in the chemical industry, that manage ecology and social sustainability beyond their company boundary and view managing supplier relations as part of their fundamental strategy [35].

The output from each region, from each orchard and even with the same technology, can differ. This is why an initial estimation of the output and cost from each orchard or the regional location of the supplying orchards must be made. This information is then analyzed and processed in order to have useful operational information. This may be difficult for some agro-food products but is already used in orange production in many regions of Mexico. These types of characterizations can be made by collaboration through a confederation of growers, trade group, sponsorship of the FC or by government and independent research bodies.

The characterization of the performance of the fields can be either an internal exercise of the different production fields or it can be an experimental one carried out by expert bodies. In the second alternative, a third body has to collect and integrate data into information that can be used by all stakeholders. This can be carried out by the use of experimental fields in order to characterize the surrounding environment and local soil production.

The information that is necessary to apply this methodology is: field production yield (expressed in tons per hectare per year) and operations cost (energy cost, agrochemicals input cost, etc.). Other important indicators may also be considered such as land and irrigation cost, but are not included in the scope of the case study of this investigation.

The most widely used technique to measure the environmental impact in the current literature on GSCM is using LCA, which matches well with the holistic systems approach of SCM. LCA can provide information on the effect of each step depending on the depth of the analysis, from process and product design to industrial systems design and even at more strategic scales, such as GSCM. For the SSP, a collaborative scenario is investigated in which information and knowhow are shared between the Focal Company and the suppliers, this is also known as Supplier Development [34]; the objective is to use the synergy created through the flow of information that helps the Focal Company make better decisions. This explains why the FC has the insight to perform a system-wide analysis such as LCA. To collect and analyze the potential data, suppliers must be willing to share information on field, plants and management practices; in turn, the centralized manager must be transparent in its measurement and evaluation techniques. This process can be divided into three steps as explained in the two following sections.

In this step, a characterization of regionally used technological packages has to be evaluated, this can be based or made at the same time as the Yield and Cost characterization process; these packages may consist of agrochemicals used, soil treatment, physical manipulation (e.g., hedging, pruning, shaping, etc.), and machinery used, among other things. During this phase, experts are needed not only to characterize the production systems at field, but also to help classify them by level of sophistication. The result should be a manageable set of categories in which an average is used as a typical example per category that describes how production systems work (e.g., "organic" production, average production and intensive production system). Although it is important to have a well-developed approach in order to classify, this falls out of the scope of this research. It is assumed that this step is performed through expert opinion; for the case study, information from a regional government-funded agricultural research center is used.

Once the categories are developed, a systematic evaluation is achieved to define the basic indicators that will be used in the modelling and optimization process. These indicators may consist of operational functions such as the average yield obtained per area, plant or tree. It can also include economic functions such as average cost per unit of product given a technological package used, which are developed during the Yield and Cost characterization; in addition, environmental impact indicators such as CO_2 emissions or eutrophication are calculated per area, plant or tree in a given timeframe, e.g., per year. The environmental impacts are evaluated by LCA. This analysis requires different levels of information provided by field and literature research, expert collaborators and dedicated LCA software tools that are commercially available.

The environmental impact assessment is then integrated in the model as well as the other indicators. The model is useful to predict the impact that a decision alternative has not only towards operational and economic performance, but also towards environmental aspects given a set of decision variables.

2.2. Partner for Sustainability: Supplier Network Model

In order to directly improve the overall performance of the Supplier Network (SN) by incorporating a long-term partnership in which an interchange of technological knowledge and risk sharing is made by contract, a multi-objective optimization formulation is proposed. This approach allows the consideration of multiple and possibly antagonistic objectives to be concurrently optimized [23,42].

The general model is described below:

Index and Sets

i	Supplier index of a set I
g	Technology package of a set G

Variables

b_i	Binary variable used to select a supplier (i)
s_i	Production capacity to be contracted per supplier (i) as a continuous measurement of land area (ha)
$Y_{i,g}$	Production yield estimated per technology package (g) used at each supplier (i) (ton/ha/yr)
$CT_{i,g}$	Production cost estimated per technology package (g) used at each supplier (i) ($/ha)
EI	Environmental impact measurement of the full set of suppliers (i) (EI unit e.g., KgCO2-eq)
EIs_i	Environmental impact estimation for each supplier (i) (EI unit/supplier)
CO_i	Cost incurred for operations for each supplier (i) ($/yr)
CE_g	Environmental cost estimated per unit of production based on technology (g) (EI unit/kg)
Cost	Cost incurred of the full set of suppliers ($/yr)
LLC_i	Lowest value of land capacity to be contracted of each supplier (i) (ha)
P	Total raw material produced (ton/yr)
PCap	Processing plant raw material requirement (ton/yr)

Objective functions

Z_1 = min (Costs)
Z_2 = min (Environmental Impacts)

The cost variable represents the cumulative cost of all orchards; this is to say the sum of the cost of each supplier given the technology package used and the capacity contracted represented by CO_i (see Equation (1)):

$$Cost = \sum_{i=1}^{n} CO_i. \tag{1}$$

The CO_i expression in Equation (2) is calculated considering the selection of a supplier, the capacity that is contracted multiplied by the cost per hectare given a given technological package, here represented by the (g) index, all of this calculated per supplier (i):

$$CO_i = b_i s_i \times CT_{i,g} \; from \; i = 1, 2, \ldots, n. \tag{2}$$

The global impact generated by all suppliers can be evaluated by Equation (3):

$$EI = \sum_{i=1}^{n} EIs_i. \tag{3}$$

In Expression (4), the environmental impact based on selection variable (b), capacity to be contracted (s) and technology package selected (g) is expressed by:

$$EIs_i = b_i s_i Y_{i,g} CE_g \; for \; all \; i = 1, 2, \ldots, n \tag{4}$$

subject to, raw material requirement of the processing plant (FC) expressed in Equation (5):

$$P \leq PCap. \tag{5}$$

A restriction on the contract specification of minimum land to be guaranteed in contract phase is represented by Equation (6):

$$s_i \leq LLC_i \text{ for all } i = 1,2,\ldots,n. \quad (6)$$

Assumption 1. *Each supplier has a given physical or contractual capacity constraint.*

Assumption 2. *Each supplier is willing to accept the technological package selected for the optimal SN in the negotiation and contracting step.*

Assumption 3. *The total quantity requirement of raw material is fixed given the capacity at the processing plant.*

It is important to mention that although this approach seeks to improve the overall supply chain, the scope of this study is yet limited since some important environmental impacts and cost producing elements related to transport distance, mode and size are neglected.

2.3. Partner for Sustainability: Supplier Network Optimization and Selection

The optimization approach proposed in this work is performed by a genetic algorithm method. This choice was made according to the flexibility of this approach to tackle problems with multiple objectives, its potential to solve problems without restriction on the type of variables, either integer or continuous, in addition to its capacity to solve linear and non-linear problems [43]. Generally, the engineering design problem tends to be of a multiobjective nature with different variables and characteristics. Other methods may be considered that can also handle multiple objectives at once with variable complexity.

The final selection process is made using a multi-criteria decision-making process that takes into account the optimal alternatives found in the Pareto front. These alternatives are found to be non-dominated solutions near optimal value, and although the decision maker may use judgment to make the final selection from the alternatives, a formal method based on TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) is proposed in this paper [44,45]. This method is based on the idea of choosing the best alternative solution from a set by analysing the shortest geometric distance from the positive ideal solution and the longest distance from the negative ideal solution. It also requires weights to be assigned per criterion and normalizes the information, so that the various alternatives are ranked. Although other ranking and classification methods exist, TOPSIS has proven its efficiency in the final alternative selection process obtained through GA [46,47].

Supplier contracting is proposed within a Contract Farming (CF) framework, where a partnership is made by a contractual agreement in order to share knowledge and risk. Through this type of contracting, the possibility of incorporating centralized decision-making regarding technology used during the farming stage is allowed because of the shared risk and growth that contract farming promotes [38]. Although the use of CF may be difficult in some circumstances and regions, in the case of many developing countries, where a large part of the production systems have not yet become intensified, this type of collaborative framework can be seen as an opportunity for both parties.

3. Results

Case Study: Orange Juice Production

The orange juice industry supply chain network serves as an illustration of the proposed methodology and raises a lot of issues of GSCM. The case study is located in the Mexican Gulf Coast region of Martinez de la Torre, Veracruz, which is the most important citrus fruit producing region in Mexico. The SSP implies orange fresh fruit supplying orchards that are to be selected as suppliers for an orange juice producing company. The case study follows the steps proposed in the methodology section. They are presented in what follows.

The regional characteristics of production systems involve four basic technological packages. These packages range from organic (1), basic (2), standard (3), to intensive (4) systems, as shown in Table 2.

Table 2. Characteristics of each type of technology package.

	Technology Package			
Agricultural Practices	**1 (Organic)**	**2 (Basic)**	**3 (Standard)**	**4 (Intensive)**
Soil loosening	0	1	2	2
Weeding	2	2	2	0
Plantation	1	2	2	1
Chemical weeding	0	1	2	5
Pruning	0	0	1	1
Trunk protection	1	1	1	2
Chemical insecticide	0	0	4	6
Chemical fungicide	0	0	4	6
Urea (N)	0	0	2	4
K_2O_5	0	0	2	4
P_2O_5	0	0	2	4
Fuel *	0	0	90.3	105.35
Communication	1	1	1	1
Harvesting	1	1	1	1

Note: Unit is in number of applications during one year; * in liters of standard gasoline.

Each technological package was studied in order to determine the mean production yield and production cost as input parameters of the modelling stage; the values are presented in Table 3.

Table 3. Yield and cost matrix per technological package.

Indicator	Unit	1 (Organic)	2 (Basic)	3 (Standard)	4 (Intensive)
Production yield	ton/ha	5	8	15	25
Production cost (contract)	$(mxn)/ha	635	1275	3064	4205
Production cost (product)	$(mxn)/ton	127	159.38	204.27	168.2

An investigation related to this case study was performed by the Research Centre on Economic, Social and Technological Aspects of International Agriculture Policies (CIESTAAM), a research institution which is part of the Autonomous University of Chapingo (UACh). The study involved specialists on agricultural issues of the region [48]. The average yield of production as well as the operational cost related to these types of technological packages and practices were determined and presented. An orange production manual for the geographical region made by the National Institute for Forestry, Agricultural, and Animal Husbandry Research (INIFAP) [49] provided the information needed to perform the LCA.

Using the information gathered during the previous steps, a LCA was carried out through the use of the specialized software tool Simapro® [50].

Table 4 shows the selected environmental impact indicators from the IMPACT 2002+ method that is adopted in the optimization phase. Global Warming Potential (GWP) is one of the most widely used and understood environmental performance indicators. This is one of the reasons why it was selected for the simulation model; other indicators related to agricultural practices such as Acidification and Terrestrial Eutrophication, among others [51], can also be used when modelling environmental performance within the proposed methodology. Key environmental indicators selection should be based on requirements and goals of the study. It must be emphasized that aquatic eutrophication was selected given the effect of chemical fertilizers, regarding water nutrient contamination [51,52]. In [53], the authors present a meta-analysis of LCA applied to orange juice production and contrast with direct findings of their own LCA study applied to a Spanish production system. In their findings, Climate Change (related to GWP) and Eutrophication (terrestrial and marine) are mainly contributed by N-fertilizers in the orange production stage. These indicators serve as an appropriate proxy for other indicators and sources (i.e., other agrochemicals) given the incremental usage behaviour described in the technological packages used in the case study (see Table 2). It is, nevertheless, important to point out that some important indicators such as human toxicity and acidization may also be appropriate depending on the crop/cultivar being produced.

Table 4. Environmental indicators output table per technology package.

Impact Category	Unit (per kg of Orange)	Technology Package			
		1 (Organic)	2 (Basic)	3 (Standard)	4 (Intensive)
Aquatic eutrophication	kg PO_4 P-lim	0	5.060×10^{-6}	1.230×10^{-5}	1.620×10^{-5}
Global warming	kg CO_2 eq	0	1.355×10^{-3}	1.149×10^{-2}	1.291×10^{-2}

The supplier network model was then developed using the information developed in the previous steps and by integrating it to the set of systems parameters gathered by the procurement analyst or model developer. This includes the following information:

- In the case of suppliers, a set of 20 suppliers is evaluated which are related to index (i) of set (I). Four technological packages are considered and integrated as the (g) index of the set (G).
- The minimum requirement for the processing plant (see Equation (5)) is set at a value of 60,000 tons of oranges, which is the capacity of a medium to large orange juice processing plant in Mexico.

Three objective functions are considered, one related to cost and two to environmental impacts:

Z1 = minimization of operational cost = min (Cost)
Z2 = minimization of CO_2 emissions equivalent = min (GWP)
Z3 = minimization of aquatic eutrophication equivalent = min (Eutro)

This cost criterion was selected since it can be viewed as useful to convince the participating potential supplier that this strategy is mutually beneficial in contrast to supplier sale prices or other forms of economic criteria such as initial investment, net present value, etc.

The input for the restriction related to minimum and maximum land area to be contracted (see Equation (6)), is presented in Table 5. A minimum value within the contract scheme stipulates that at least half of the capacity is contracted in the case of a selected supplier. This is done to promote the supplier participation in the type of proposed collaboration, as well as to reduce the number of suppliers that the optimization process can select.

Table 5. Relation between suppliers and respective field size that can be contracted for use.

Supplier	Contractible Hectares (t_i)	Supplier	Contractible Hectares (t_i)
1	226.48	11	50
2	101.38	12	298.82
3	190.73	13	107.57
4	650.81	14	115.81
5	43.12	15	69.11
6	512.61	16	258.94
7	43.05	17	273.76
8	560.81	18	250.52
9	26.29	19	221.52
10	22.97	20	17.75

Optimization is then carried out using the MULTIGEN®genetic algorithm extension library [54]. The optimization simulations parameters used are shown in Table 6. The population size and number of generations was empirically evaluated by a preliminary analysis showing that a ratio roughly set at 20 individuals per variable, and doubling of population size is effective within the MULTIGEN environment. The crossover and mutation rates were set at default values as suggested in [54]. The use of the NSGA II optimization algorithm is selected given its capacity to find a non-dominated set of alternatives to develop the Pareto fronts needed [55].

Table 6. Optimization run parameters.

Parameters	Values
Population size	400
Number of generations	800
Algorithm	NSGA II
Crossover rate	0.9
Mutation rate	0.5

The optimization was run five times in order to validate and search a wider area of the feasible space, and this generated a set of 192 alternatives to be analyzed. Figure 3 shows a three-dimensional scatter plot where the vertical axis is Cost (in Mexican pesos or $MXN), the right axis is GWP (in kg CO_2 eq) and the depth axis is Eutrophication (in kg PO_4 P-lim).

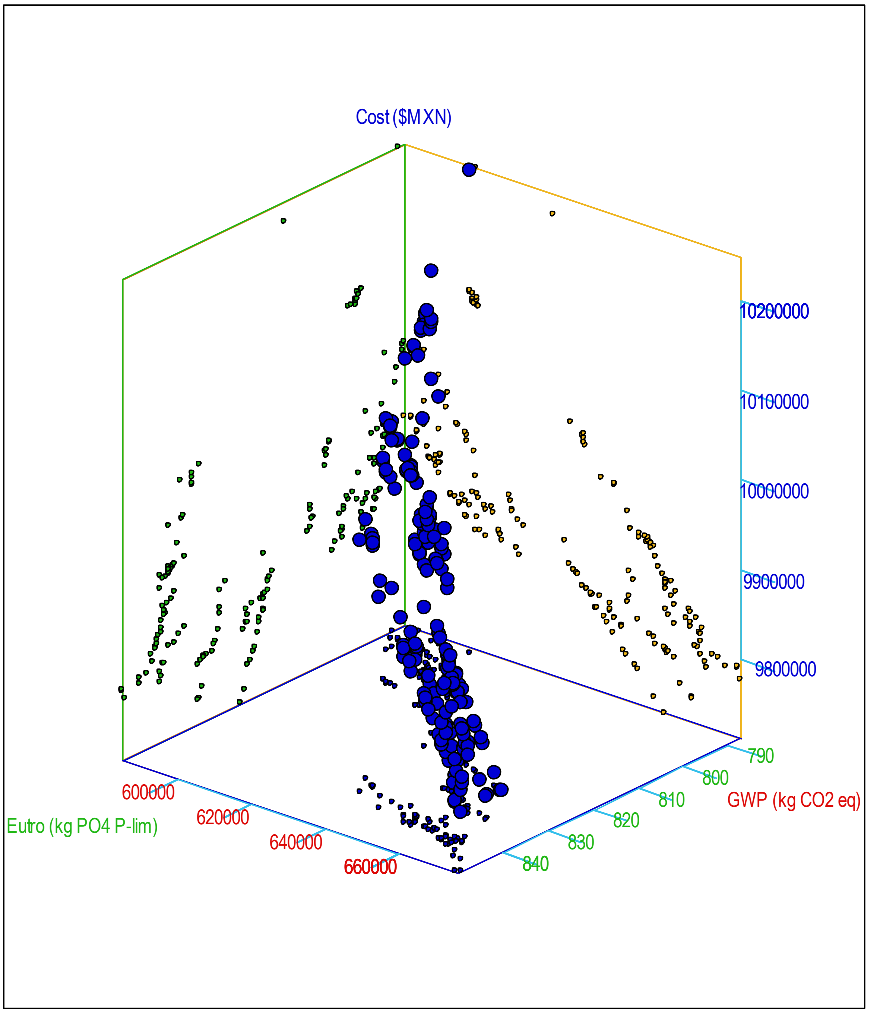

Figure 3. Three-dimensional scatter plot of all five Pareto Fronts.

Figure 3 exhibits the set of the different series of Pareto front runs. As this is a set of many Pareto fronts that were not evaluated concurrently, there are dominated points within the data set, which must be eliminated prior to applying the final selection.

Given that the resulting set of five Pareto fronts does not show a clear optimal decision alternative or region, the use of a decision-making tool becomes even more necessary. This final selection process is carried out through the use of a modified TOPSIS method proposed by Ren et al. [45] that consists of ranking the alternatives through a comparison with the values of the "ideal" curve. Before applying the TOPSIS method, a selection is made in order to keep only non-dominated alternatives from the five Pareto fronts. This series of steps is described below:

$$U\{\text{Pareto Front runs } i = 1, \ldots, 5\} \rightarrow \text{Pareto } \{U\} \rightarrow \text{TOPSIS } \{\text{Pareto}\}. \quad (7)$$

By applying steps 1 and 2 of the abovementioned procedure, leading to the Pareto of the Paretos (i.e. Pareto {U}), a lower number of 46 non-dominated alternative solutions is obtained. From them, the TOPSIS method [45] is applied in order to find the best ranked values. Figure 4 shows the resulting values with the location of special TOPSIS values called 1, 13 and 45, that correspond to the overall top-ranked one, the best TOPSIS value in relation to GWP and the best TOPSIS value in relation to Eutrophication, respectively.

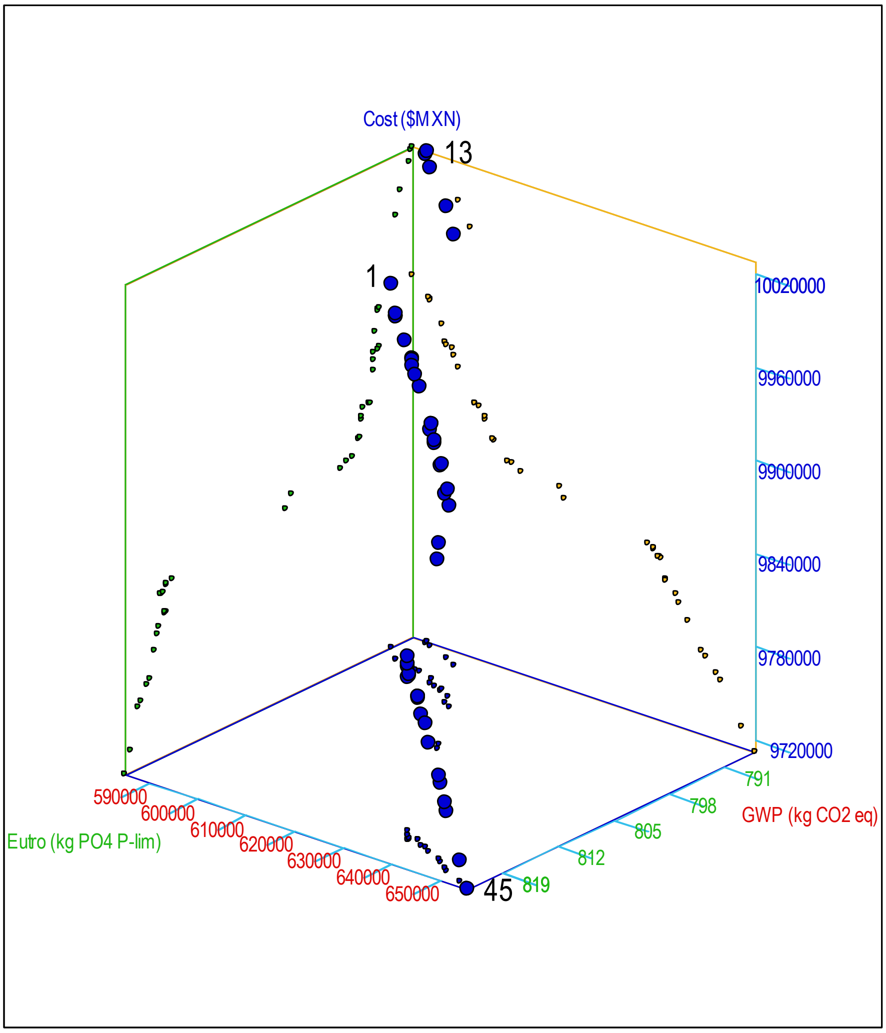

Figure 4. Three-dimensional scatter plot of the Final Set with TOPSIS ranked points.

Figure 4 shows that the top-ranked TOPSIS value is in the higher cost range. This solution is yet selected due to the trade-off against the environmental criteria. The improvement of cost is low, relative to the gains in environmental performance.

Table 7 presents the values for each criterion for some significant TOPSIS ranked alternative: number 1 (TOPSIS 1), the 13th (TOPSIS 13) and 45th (TOPSIS 45) values. TOPSIS 1 has the best compromise since it provides the best value for GWP and only differs from the best value for Eutrophication criteria by 0.33% (TOPSIS 13). Its cost is slightly higher of 2.35% of the best cost criterion performing alternative (TOPSIS 45). The three points can also be visualized in Figure 4 where TOPSIS 13 and 45 are at the extremes, whereas TOPSIS 1 is located at the upper part of the scatter plot.

Table 7. TOPSIS evaluation per criterion.

Criterion	TOPSIS 1	TOPSIS 13	TOPSIS 45	Discrepancy 1 vs. 13	Discrepancy 1 vs. 45
Cost ($MXN)	9,945,457	10,027,688	9,712,002	0.83%	2.35%
GWP (kg CO_2 eq)	585,024	587,981.24	655,538	0.51%	12.05%
Eutro (kg PO4P-lim)	789	787.09	823	0.33%	4.26%

Table 8 presents a comparison between the TOPSIS 1 solution and the TOPSIS 1 of a sample taken from the first Pareto front run at the 10th generation. The 10th generation was selected because it was the first generation in which all the individuals (solutions) are in the feasible space.

Table 8. Comparison between TOPSIS 1 and samples from 10th generation optimization value of the first Pareto front.

Criterion	TOPSIS 1	TOPSIS 1 of Sample PF		Average of Sample PF	
		Value	Discrepancy (%)	Value	Discrepancy (%)
Cost ($MXN)	9,945,457	10,348,080	4.05%	11,358,729	14.21%
GWP (kg CO2 eq)	585,024	669,783	14.49%	790,669	35.15%
Eutro (kg PO4P-lim)	789	849	7.57%	973	23.32%

The differences that can be observed are significant for all criteria, which justifies the application of the optimization procedure. A comparison between the average values of the sample is used in order to visualize the improvement that can be achieved through Partnership for Sustainability method, exhibiting a significant performance between 14% to 35% for the different criterion.

Supplier contracting is then the final stage in the selection process. For the case study, the optimization results then allow to select the suppliers, the type of technological package to use, and the area of land to be guaranteed in the final contract. Table 9 displays the final set of values for the decision variables for TOPSIS 1 alternative. It can be first observed that it implies all suppliers, since the optimization search leads to select different types of technologies of low yield but with a better overall performance. The second interesting point is that the mix of technologies used does not include technology package 3, which is the most commonly used technological package in the region. It must be also highlighted that there was only one field of a small area with a technology package type 1. This is most probably due to the fact that technology package 2 yields more products for a similar environmental impact performance.

The application of the methodology results in a set of alternatives given by rank. Although other external factors such as agricultural, economic and environmental policies have to be considered in the final judgment, the decision aid provides the insight needed for an objective and efficient supplier selection tool.

Table 9. Decision variable results for TOPSIS 1.

Supplier	Technology	Selection *	Land Area
1	2	1	217.630
2	2	1	100.407
3	4	1	188.867
4	2	1	649.984
5	4	1	42.206
6	2	1	506.885
7	4	1	42.982
8	4	1	490.285
9	4	1	25.740
10	4	1	20.785
11	4	1	48.021
12	2	1	297.277
13	4	1	107.083
14	4	1	113.144
15	4	1	68.255
16	4	1	245.091
17	2	1	271.078
18	4	1	235.275
19	4	1	204.422
20	1	1	14.454

* 1 = supplier selected; 0 = not selected.

4. Discussion

Partnership for Sustainability can be a useful tool in tackling the supplier selection problem by providing a paradigm shift regarding collaboration as a means to improve overall performance of sustainable food supply chains. The steps laid out in this paper provide a roadmap to improve and incorporate different ways on how GSCM may be used and structured to overcome weaknesses in conventional management practices when confronting strategic long-term decisions such as the Supplier Selection Problem. The case study that is presented may prove useful in understanding how to incorporate modelling and optimization within the Guidance provided by ISO20400 on Sustainable procurement. Reviewing Table 1 where a 7-step supplier selection process has been developed. Pre-selection and Short listing stages, knowing that the long-term goal is to develop collaborators and procurement staff can help develop useful knowledge for better judgment in favor of organizational attributes that will be highly valued in later stages (e.g., organizational culture, reputation, supplier local socio-economic indicators, etc.). This can feed the Supplier characterization stage that takes environmental performance as an attractive attribute. Some indicators could be used if they comply with norms and standards (e.g., organic production, ISO14000 Environmental management, ISO26000 Guidance on social responsibility). This will allow the FC to create a supplier network model that has many design alternatives, creating a wider space to optimize and choose from in the final stages (i.e., supplier network optimization and selection). Finally, this paper presented a complete and comprehensive case study in order to illustrate the capabilities and limitations of the proposed approach, and provided insight on what type of information is required and how it could be used in order to develop feasible and non-dominated optimal solutions.

The case study also illustrates some of the patterns one could confront when developing other specific green supplier selection models based on the methodology. Although it may have some areas to improve, it provides the foundation for continued work to analyze and integrate important factors in the decision-making process in the context of collaboration with suppliers that may become partners.

Some of the main perspectives to this paper are firstly, the further development and integration of contract policies into the supplier selection process methodology. This is a difficult task since information flow and synchronization among parties are not always functional. Yet exploring the potential of Contract Farming and collaborative farming in the context of the SSP may be valuable in some organizations. A second opportunity is to target the information collection, in the sense of better establishing which type of information a buyer requires from its potential and current suppliers, in order to make the best decision and to continuously maintain an effective supplier network.

Finally, an important perspective is to integrate the results of this model into a global green supply chain optimization model that may use a similar approach for visualizing and solving the other large-scale strategic challenges of GSCM.

Author Contributions: Conceptualization, C.A.-P. and M.A.M.-A.; investigation, A.A.A.-L.; data curation, K.C.A.-S.; writing—original draft preparation, M.A.M.-A.; writing—review and editing, C.A.-P.; visualization, A.B.-S.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

ASC	Agro-food Supply Chain
CF	Contract Farming
EI	Focal Company
GSCM	Green Supply Chain Management
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
MCDM	Multiple Criteria Decision Making
MOO	Multi-Objective Optimization
MS	Multiple Strength
M-TOPSIS	Modified Technique for Order of Preference by Similarity To Ideal Solution
NSGA	Non-Dominated Sorting Genetic Algorithms
PfS	Partnership for Sustainability
SC	Supply Chain
SCM	Supply Chain Management
SCND	Supply Chain Network Design
SN	Supplier Network
SS	Single Strength
SSP	Supplier Selection Problem
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution

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