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Sustainable Multi-objective Planning of Biomass Conversion Systems under Uncertainty

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Recently, the biomass has gained considerable attention as a feedstock for energy production because of its attractive characteristics, including its availability as a renewable resource. However, the biomass can be subjected to several uncertain factors such as the availability, market cost and composition; thus, it is worth noting that the uncertainty in the raw material can affect drastically the final supply chain configuration of the product. Therefore, this work presents a new approach for the optimal planning under uncertainty for a biomass conversion system involving simultaneously economic and environmental issues. In this context, the EcoIndicator99 method was used to assess the overall environmental impact in the entire supply chain. Additionally, the economic aspect takes into account all the costs associated to the different activities as well as the costs for raw materials and the sale of products. The proposed method considers the uncertainty involved in the supply chain through the raw material price by the stochastic generation of scenarios using the Latin Hypercube method followed by the implementation of the Monte-Carlo method for determining the optimal structure for each sample. Furthermore, with the proposed approach is possible to select the more robust structure for the supply chain based on statistical data. On the other hand, the proposed approach incorporates an analysis based on the standardized regression of the uncertain coefficients within the supply chain to determine the magnitude in which the uncertain data affect the value of the considered objectives. The proposed approach was applied to a case study for a distributed biorefinery system in Mexico, considering 6 suppliers, 6 processing facilities as well as 5 distribution centres. Besides, 9 raw materials were contemplated to obtain 5 different products through 2 processing routes.

1. Introduction

Biomass appears to be a viable raw material to replace oil for the production of several valued-added products, especially biofuels through biorefineries. However, its implementation requires the exploration of several aspects, including the selection of feedstocks, processing routes, products, harvesting sites, processing and markets, as well as numerous other sustainability criteria. Recently, the optimization of supply chains (SC) associated to biorefineries and the multi-objective optimization of SC based on biomass conversion that include environmental and sustainability implications have gained the attention of the industry and academia. With respect to the consideration of the environmental issue in applications for supply chains, Czarnowska et al. (2014) analysed several methods to measure the environmental impact such as the methods based on life cycle assessment. Also, with respect to the multi-objective optimization, Kravanja and Čuček (2013) presented two multi-objective approaches for synthesizing sustainable systems for biogas production, both approaches considered a single product and the change over time was not taken into account. El-Halwagi et al. (2013) introduced a new approach for the incorporation of safety criteria into the selection, location, and sizing of a biorefinery.

More specifically, for the optimal planning of supply chains, Koltsaklis et al. (2013) presented a mixed integer linear programming model for the optimal planning of a national power generation system. In addition, a mathematical model able to incorporate economic, environmental and social aspects was

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developed by Ng and Lam (2013). Additionally, Čuček et al. (2014) proposed a simplified and practical version of an objective dimensionality reduction method within the multi-objective optimization framework. Corsano et al. (2013a) developed strategies to take decisions about the topology, planning and design of the processing facilities in a supply chain to satisfy the product demand with the minimum cost. Also, Corsano et al. (2013b) proposed a mixed integer linear programming model for the optimal design and production scheduling of a supply chain to produce bioethanol. Finally, Yue and You (2015) presented a mixed integer nonlinear programming model to assist decision maker about the investment when the entities of a supply chain based on biofuels do not cooperate between each other.

On the other hand, the uncertainty is an important aspect to take into account in the supply chain design considering the stochastic nature associated to the problem. This way, several works have considered the optimization under uncertainty applied to bioprocess (Morales-Rodriguez et al., 2012), the optimal planning under uncertainty (Hansen et al., 2011) and uncertainty on scheduling (Wang and Rong, 2010). It is worth noting that a supply chain design under uncertainty allows to obtain a final configuration able to include the change of the different uncertain parameters associated to the optimal planning of the supply chain. However, the inclusion of the uncertainty in the supply chain design problem causes a significant increase in the problem size, complexity, CPU time and the invested resources (Quaglia et al., 2013).

Therefore, this work proposes a new mathematical programming approach for the optimal planning and design of a distributed system of biomass conversion taking into account the economic and environmental issues and the uncertainty associated to the supply chain simultaneously. The economic objective was considered through the net annual profit, while the environmental objective considered the life cycle assessment for the entire supply chain in EcoIndicator99 units; finally the uncertainty analysis was done by the stochastic generation of scenarios on the raw material price using the Latin Hypercube method followed by the implementation of the Monte-Carlo method. It is important to quote that the mathematical approach considered the interactions between the different entities of the supply chain, the dependence of the time on the inventory levels, several processing stages to process the byproducts, as well as several products and raw materials to be selected.

2. Outline of the Addressed Problem

The proposed approach is a multi-objective optimization model, which allows obtaining the configuration of a distributed system of biorefineries considering environmental and economic aspects and simultaneously accounts for the uncertainty associated to the raw material prices. This way, it is given a set of biomass supplier regions, processing facilities and consumers as well as a portfolio of raw materials and products and a set of processing technologies for different processing steps. Additionally, it is considered the raw material price as uncertain parameter, which can affect the topology of the supply chain. Then, the problem addressed consists in determining the topology of the supply chain able to support the changes in the raw material price in order to simultaneously maximize the net annual profit and to minimize the environmental impact. It should be noted that the present work considers the mass balances between the different entities of the supply chain for different periods of time, taking into account the storage in the different allocations of the system.

3. Mathematical Formulation

The proposed mathematical programming formulation is based on a state task network representation for the distributed system of biorefineries; where the states are represented by the raw materials, products and byproducts in the different places such as raw materials in any processing plant as well as products in any consumer. On the other hand, the tasks are the different activities that consume a given time such as the transportation between the different entities of the supply chain, processing or production of raw material. Each activity is defined by a binary variable to indicate that is accomplished in a given period of time. Additionally, the use of any facility (suppliers, processing plants or consumers) is associated to a specific binary variable. The model considers mass balances for raw materials and products in the different locations of the distributed system, the equations also include relationships for storage of materials, maximum and minimum limits for transportation and processing, and constraints for availability of raw materials. Also, this model considers the economies of scale for the production technologies and the seasonal dependence of the potential bioresources as feedstocks for the distributed system of biorefineries. It should be noted that most of the equations for the economies of scale and capital costs are nonlinear, which are linearized in several intervals (Bowling et al., 2011) to formulate the model as a Mixed Integer Linear Programming (MILP) problem. Additionally, two objective functions are taken into account. The first objective function consists in the maximization of the net annual profit, taking into account the revenue for the sale of products minus the operational, capital, transportation, storage and production of raw material costs. The capital cost is given by the installation cost of the processing facilities for each one of the processing technologies. This objective function can be written as follows:

$$Net\,Profit = Rev^{\substack{Sales\\product}} - C^{Operational} - C^{Capial} - C^{Transportation} - C^{Storage} - C^{Raw\,Material} \tag{1}$$

The second objective function is given by the overall environmental impact of the entire supply chain. This environmental impact was measured by the EcoIndicator99 method based on the life cycle analysis. This way, the environmental objective functions is formulated as the environmental impact by the production of raw materials plus the environmental impact for processing, transportation of materials and the use of final products.

$$EI^{overall} = EI^{\substack{Raw\,Material\\production}} + EI^{Processing} + EI^{Transportation} + EI^{\substack{Use\\products}} \tag{2}$$

It is important to mention that there are several options to assess the environmental impact as measurement of the carbon footprint, greenhouse gas emissions, depletion of waste and toxicity in the water and land. However, the Ecoindicator99 method considers 11 damage categories, between these are the damage to human health caused by climate change and the damage to the ecosystem through emissions. Both of these categories are directly associated to the carbon footprint. This way, the Ecoindicator99 for the raw material production takes into account the emissions for the growth of biomass, use of fertilizers, water use and transportation into the harvesting site. The necessary data to assess the environmental impact were collected from the database of the SIMAPRO 7.1 software for the value of the unitary Ecoindicator99 for the substances involved in the supply chain. Additionally, the inventory of the process was obtained from data reported by Santibañez-Aguilar et al. (2014).

4. Solution Approach

In order to select a configuration of the supply chain considering the uncertainty associated, it is needed to define the framework for the solution. This way, Figure 1 illustrates the proposed solution approach. The first step is to define the superstructure of the mathematical model; this is necessary to know the sections of the process, raw materials, products, processing stages, variables, parameters and constraints. The second step involves determining the uncertain parameters and variables from historical information as well as published information in the literature. In this study, the selected uncertain parameters are the raw material prices since these parameters can affect seriously the final configuration of the supply chain. The third step consists in sampling N scenarios for the uncertain parameters by an adequate method; in this case, the uncertain parameters are distributed uniformly between upper and lower limits using the Latin Hypercube method followed by the implementation of the Monte-Carlo method because this produces a representative distribution without a large number of samples and the CPU time is an important factor to solve this type of problems. The upper limits correspond to the mean plus 1 standard deviation (around 20% from mean value) and the lower limits take the value of the mean minus 1 standard deviation (approximately 20% from mean value). In the fourth step, the sample scenarios are employed to solve a deterministic problem in GAMS for each of the samples that include the different prices for the selected raw materials, which provide the process structure with the maximum value of the net annual profit. It should be noted that each deterministic problem is subjected to an upper limit for the environmental impact to implement the ε-constraint method for a multi-objective optimization. The results of the deterministic optimization problem generate the optimal configuration of the supply chain for each sampling. Thus, the fourth stage generates a number of optimal configurations equal to the number of sample scenarios for the uncertain parameters. In the fifth phase the selection of the optimal process configuration relies on statistical analysis such as the mode among the samples since each solution represents an optimal solution according to the step 4. Whether there are two or more configurations with the same number of occurrences, the final decision is taken based on the value of the economic objective. Finally, the optimal configuration of the supply chain is reported with the values of the net annual profit and the environmental objective. Then, in sixth step the value of the upper limit for the environmental impact is changed to come back to the step 4. It is important to mention that it is necessary to implement a screening of the environmental constraint to obtain the Pareto curve applying the ε-constraint method.

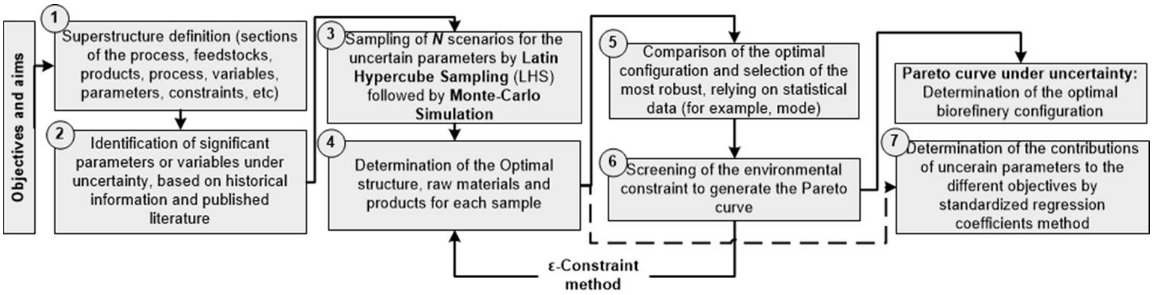

Figure 1: Proposed methodology for the optimal multi-objective planning under uncertainty

Additionally, the seventh step is proposed to perform a statistical analysis based on the standardized regression coefficients method to identify the contribution of each uncertain parameter or variables on the selected objectives or factors. This stage is important to know the raw materials with more contributions to the objective function to include or exclude raw materials for future analysis because the CPU time depends on the number of variables and parameters when the uncertainty is taken into account. Also, the stage 7 is useful to predict the behaviour of the supply chain topology when the availability of some raw material changes drastically (e.g. climate conditions).

5. Results

The proposed method was applied to a nationwide study for Mexico considering 6 biomass suppliers, 6 processing plants and 5 consumers. Moreover, 9 raw materials were contemplated to obtain 5 different products through 13 processing routes in the first processing stage and 10 processing technologies for the second processing stage. It should be noted that the proposed raw materials, products, processing routes and locations have the same possibility to be selected; although the approach is able to choose the best combination of them in order to find the optimal solution for the environmental impact and the profit. Also, it is important to mention that the uncertain parameter was the raw material price, which was considered by the generation of 100 different samplings using the Latin Hypercube method. The data for the case study were taken from Santibañez-Aguilar et al. (2014).

The problem was formulated as a mixed integer linear programming model in GAMS, where each scenario is solved. The software MATLAB was used for the generation of scenarios and the statistical analysis to select the structure of the supply chain and carry out the standardized regression coefficients. The model was solved using a computer with processor Intel Core i7-4700MQ at 2.40 GHz. The average CPU time for solving the MILP per sampling was 12 min, for the statistical analysis of the solutions was 70 minutes. The MILP consists of 1,152,679 constraints, 779,791 continuous variables and 200,660 binary variables.

Figure 2 shows the trade-off between the net annual profit and the environmental impact for the different selected supply chain configurations. It is important to note that each point of the Pareto curve represents the selection of the more robust supply chain configuration (larger mode in the samples) obtained from the uncertainty analysis.

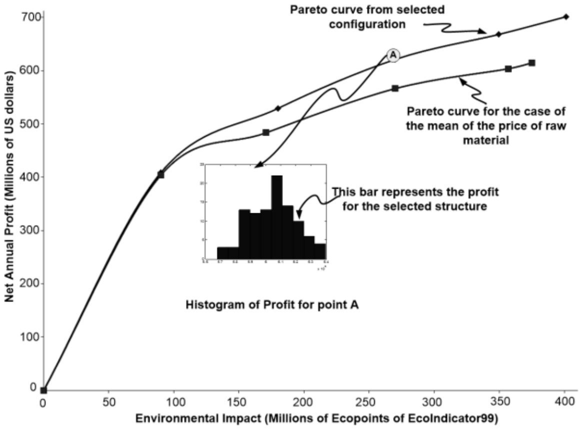

Figure 2: Pareto curve for the supply chain design under uncertainty

Besides, Figure 2 shows the Pareto curve between the environmental impact and the annual profit for a special case where the uncertainty is not taken into account since the uncertain parameters are equal to the mean values. In other words, the aforementioned Pareto curve is the solution of the deterministic case. Notice that the Pareto curve considering uncertainty presents better values for the net profit and the environmental impact since this curve takes into account the interaction of different uncertain scenarios for each point and the selected structure for each point may be the result of a different scenario. Additionally, the point A was selected in order to show the final configuration of the supply chain. This point represents a final profit around 600 M $US and a value for the environmental impact of 260 M of eco points of EcoIndicator99.

Additionally, Figure 3 illustrates the general configuration of the supply chain. This way, sugar cane, sorghum grain, sweet sorghum and corn grain were selected from a total of nine raw materials to be distributed to the different processing facilities. It should be noted that five products were proposed to be produced; however, Figure 3 shows that the processing plants only produce ethanol and butanol through processing routes. It can be possible due to the production of ethanol and butanol presents a better value for the objective functions considering the uncertainty in the raw material price. These products are sent to the consumers that in this case are 3 with different fulfilled demands. On the other hand, Figure 4 illustrates the different processing steps for the production of ethanol and butanol for the processing plant in Salamanca for the configuration of Figure 3. Here, it is possible to observe that three processing routes are selected to produce butanol as well as one technology to obtain ethanol in the first processing stage. Additionally, one technology is able to produce ethanol in the second processing stage.

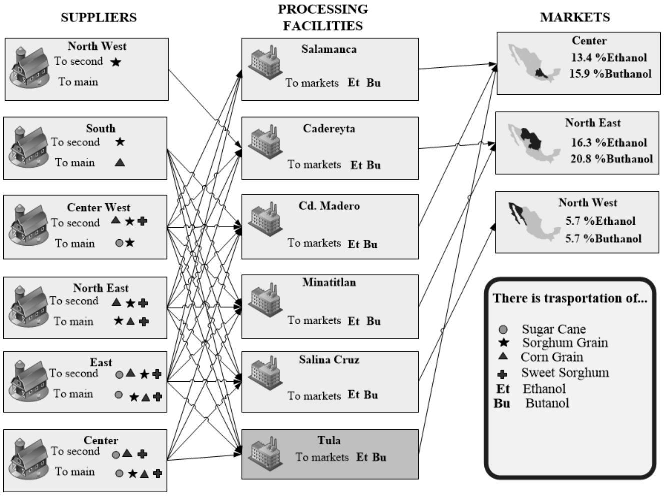

Figure 3: General configuration for the point A of Figure 2

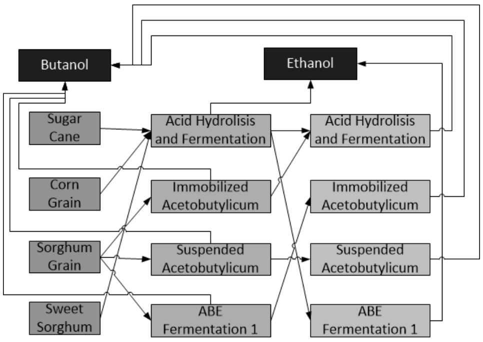

Figure 4: Representation of the processing activity in facility of Salamanca of Figure 3

6. Conclusions

This paper has proposed a new method for the supply chain optimization of biorefinery systems under uncertainty. The uncertainty was considered by stochastic generation of samplings done through the Latin

Hypercube method followed by the implementation of the Monte-Carlo method. The proposed approach simultaneously considered the economic and environmental objectives. The multi-objective analysis depicted that the curve formed from the mean values for the price of raw material presents worst values for the net profit and the environmental impact than the curve that considers uncertainty, which implies that the uncertainty in the raw material prices affect in a positive form the final values of the objectives for the selected distribution. It should be noted that the model works with any distribution data and it is possible to accomplish a sensibility analysis to illustrate the effect of the distribution data in the final topology of the supply chain. The application of the proposed approach to a case study from Mexico can be useful to identify the interaction between these contradict objectives, and it gives the opportunity to the decision maker to take better decisions about of the design of the distributed systems of biorefineries when the raw material prices or other parameters present variations.

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