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A facility-location model for biofuel plants: Applications in the Colombian context

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ABSTRACT

To reduce the logistical and operating costs for biofuel plants, it is important to make a strategic decision to select the proper site for a new facility. Due to the facility's complexity, the facility-location problem must consider the supply-chain structure, involving the material flow from suppliers to customers. This paper proposes an optimisation framework that combines the process design and configuration of the supply chain using an MILP (mixed-integer linear programming) formulation. The model was applied to locate a second-generation bioethanol plant in Colombia that uses an agricultural residue known as Coffee-CSs (coffee cut stems). The experimental results indicate that placing a processing plant at Ibagué city results in the best profitability. A post-optimisation analysis indicated that even for a long period, the location decision did not change.

1. Introduction

Biofuel production has gained worldwide interest due to its growth in recent years, as a result of governmental policies that aim for the gradual substitution of fossil fuels. The European Parliament and the United States Congress through the directive 2009/28/CE [1] and the EPAct 2005 [2], respectively, have supported the increase in biofuel-based energy production as a means to reduce fossil-fuel dependence, as well as for its effects on global warming [1,2].

Depending on the type of biomass, biofuel production can be categorised as first, second or third generation [3]. First-generation biofuels utilise feedstocks that are mainly used for animal and human food. Although this type of biofuel generation is the most efficient and profitable, it has a negative impact on global food availability. In contrast, second- and third-generation biofuels appear to present an innovative approach to eliminating the inconvenience regarding food security; however, they are less profitable than first-generation biofuels. For that reason, this trade-off (food security *vs.* profitability) has received a large amount of attention from the scientific community, specifically in research fields such as technology selection and process optimisation [4], feedstock yield [5], environmental benefits [6] and logistical issues [7,8].

Studies on SCM (supply-chain management) for biofuel production show that the majority of work has been aimed at the analysis of upstream levels [3]. However, recent studies have provided enough evidence that multi-echelon SCs lead to the integration of all of the research fields mentioned. Furthermore, such studies undertake different decision levels, in particular the operational [9], tactical [10], strategic [11] and integrated [12,13] levels.

Synthesising the recent research on the biomass SC (supply chain), one can identify the use of optimisation models as a common method to formalise the multi-echelon networks while considering the “integrated” category of decision levels. In particular, MILP (mixed-integer linear programming) appears to be the prevailing optimisation framework [14] and involves multiple decision variables, such as the capacity, facility location, technology selection, number of facilities, biomass type and other logistical variables (transport, biomass flow, biofuel flow, warehousing, etc.) [15,16].

The design of second-generation optimisation models, which have been less treated in the literature than first-generation optimisation models [17], presents different features due to its

Abbreviations: Coffee-CS, coffee cut-stem; SC, supply chain; MILP, mixed-integer linear programming.

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application context (environmental/social politics and geography characteristics) and feedstock availability. Therefore, a brief review of several of these features is shown in Table 1. The first and second columns in the table depict the optimisation-model features, and the third column provides the most commonly used categories within the analysed features. The table also organises several relevant contributions according to the categories examined.

As seen in Table 1, the economic criteria are the most common objective function defined for biofuel SC optimisation, and studies using mixed criteria (economic and environmental) are less common. In addition, regarding the biomass type, a few papers have addressed biofuel production exploiting forestry resources. Interestingly, all of the papers examined indicate domestic markets as a final destination of the biofuel production. Based on the number of studies, it is clear that the sensitivity analysis has not been a frequent issue in biofuel SC modelling (as seen in Ref. [22]). Finally, the majority of the optimisation models begin from a previously collected dataset (data are taken from government institutions, earlier studies and national databases).

To connect our efforts on the biofuel SC to the research field, this paper is focused on the design of an optimisation model under the specific conditions relevant to an actual Colombian context. As noted by other authors, the present research develops an MILP involving the processing plant number, the facility location and a materials flow that integrates multi-echelon SC. Despite these similarities, the proposed model includes the following characteristics:

- The biofuel is produced from coffee cut stems (Coffee-CSs), a crop residual that has not been studied in the SC design, notwithstanding its huge availability in Colombia.
- Most of the previous studies assume the plant capacity and processing-technology yield as the input parameters (the process design is considered a *black box*), whereas the model presented implements the professional software *Aspen* that is aimed at providing reliable input data.
- The optimisation model considers one stage in which biofuel (e.g., EtOH) and petroleum-based fuel (e.g., gasoline) are blended. In particular, this stage is introduced into the model as a constraint over the solution space; meanwhile, most studies assume this operation is an input parameter.
- In contrast to the studied papers, the proposed model considers two fates for the final products: the domestic and the international markets. This consideration is consistent with the national policy aimed to increase the Colombian participation in the biofuel global market. It should be considered that, after Brazil, Colombia is the second largest Latin American biofuels producer [23].
- Due to uncertainty in the final-market demand, a post-optimisation analysis it is developed, in which several forecast statistical methods were applied to estimate the effect of the demand over decision variables in the long-term.

A real-life case study was selected for the model application, for which five location alternatives were considered in the set of possible locations. The experimental results, using an exact optimisation algorithm (CPLEX) implemented in the commercial software package *GAMS*, provided sufficient evidence to place a processing plant at Ibagué city. This location decision implies a production capacity ranging from 3000 to 4000 t/year. The sensitivity of the decision variable values, in particular the plant location, was analysed against the demand variability within a five-year time horizon.

This paper is structured as follows: Section 2 presents a brief review of the biofuel production in Colombia. Subsequently, the model structure and a detailed explanation of its components are provided in Section 3. A case study is solved using well-known computational tools in Section 4. Finally, in Section 5, the conclusions and future research tasks are outlined.

2. Biofuel production in Colombia

Biofuel production is one of the strategic and growing sectors in the Colombian economy [24]. Colombia has a long tradition in agricultural development, and its soil availability is significant; this enables huge biomass generation that leads to formidable opportunities for new sources of energy generation. Furthermore, biofuel production not only involves the reduction of the country's petroleum-based fuel dependency, but it is also important in job creation, especially for rural regions, where the majority of the poor population of Colombian society is located [25].

Therefore, the Colombian government has approved a large number of regulations related to biofuel prices, production, transportation and storage, mixing rate with fossil fuels and environmental implications [24]. The aim of these regulations is to create incentives to promote the growth of the national production capacity, but in balance with the environment. Reference [26] states the importance of increasing the biofuel-production capacity in the

Table 1
Several optimisation model features for the second-generation biofuel SC.

		References	[18]	[15]	[19]	[13]	[16]	[20]	[9]	[21]
Features	Decision variable	Capacity	x	x	x	x	x	x		x
		Location	x	x	x	x	x	x		x
		Technology	x	x	x			x		
		Plant number	x	x	x	x	x	x		
		Biomass type		x	x		x			
		Multi-period	x	x						
		Logistic operation	x	x	x	x	x		x	
	Objective function	Economic		x	x	x	x	x		
		Environmental							x	x
		Mixed	x							
	Biomass type	Forestry					x	x		
		Crop residuals	x	x	x	x			x	x
	Final market	Domestic	x	x	x	x	x	x	x	x
		International								
	Sensitivity analysis	Yes		x	x		x	x		
		No	x			x			x	x
	Data input	Known source	x	x	x	x	x	x	x	x
		Estimation						x		