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Towards a comprehensive model of a biofuel supply chain optimization from coffee crop residues

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ABSTRACT

Biofuel production from agricultural waste has been identified as a promising strategy in the field of renewable energy. This topic involves complex mathematical modeling tasks such as feedstock characteristics, biorefinery location, capacity strategy and material flows. This paper proposes a Multiple Objective Mixed Integer Linear Programming model (MOMILP) for the design of a sustainable supply chain using multiple agricultural residues. The proposed comprehensive model is utilized in a case study in Colombia, using coffee crop residues. Computational results show the model's robustness as a decision-making tool, which allows the projection of a flexible supply chain structure in the long term.

1. Introduction

According to Azadeh and Vafa Arani (2016), the biofuel market has emerged as a possible solution to the energy and environmental crisis affecting the planet. In particular, biofuel production from agricultural waste has been identified as a promising energy strategy (Ng and Maravelias, 2016). However, the integrated analysis of strategic and tactical decisions, from a sustainability approach, poses major challenges regarding supply chain network design (SCND) (Costa et al., 2017; Quek and Balasubramanian, 2014). From the mathematical point of view, at least three main challenges must be considered: 1) feedstock characteristics; 2) capacity allocation and biorefinery location decisions; and 3) supply chain sustainability.

Feedstock characteristics have a significant influence on biofuel supply chain network design (BSCND) (You et al., 2012). Depending on raw material perishability, seasonality, availability, pre-treatment conditions, and storage requirements, it is foreseen that overall supply chain performance fluctuates from very poor to suitable values. Indeed, due to their seasonal behavior, agricultural residues are only available at certain times of the year, and are generated in varying amounts. This situation requires the use of several residues in order to meet conversion-plant capacity. Therefore, proper inventory planning in gathering centers is an important condition, in order to guarantee constant material flow toward biorefineries (Ng and Maravelias, 2016).

Capacity allocation and facility location (gathering centers and biorefineries) are two dynamic strategic decisions that must be carefully analyzed in the long term, because they depend on demand fluctuation and supply constraints (Ivanov and Stoyanov, 2016). Therefore, in SCND, capacity strategy (expansion and contraction), which in turn necessitate the opening and closing of conversion-plants in different regions (location decisions), should be evaluated so as to provide a more realistic strategic investment plan for decision makers (Lee et al., 2017).

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According to Slack and Lewis (2011), "*Capacity strategy includes a number of interrelated decisions, which include defining the overall scale of the operation, the number and size of the sites between which capacity is distributed, the specific activities allocated to each site, when capacity levels should be changed, how big each step change should be, and the location of each site*". Hence, in order to make realistic strategic and tactical decisions, SCND should consider a dynamic capacity strategy (changes in long-term capacity) due to its effects on other structural decisions (e.g. facility location, transport and material flows) as well as on the performance goals (economic, environmental and social). However, our literature review shows relevant research gaps on this SCND topic.

A third defiance is to achieve supply chain sustainability. Due to the growing concern regarding environmental and social impacts generated by logistic operations (transport, storage, production, etc.), BSCND, with a sustainable approach, has become the subject of intense interest in the literature (Bairamzadeh et al., 2016; Pishvaee et al., 2014; You et al., 2012). Therefore, achieving an appropriate balance between the different conflicting dimensions of sustainability (economic, environmental, and social goals), is a matter that must be frequently addressed in BSCND.

On the other hand, there are many studies on BSCND from agricultural residues, forest residues and urban waste. However, in the particular context of agricultural residues, there exist concerns about raw material availability to keep operations continuity in the biorefineries. For instance, a coffee stem is a residue obtained from crops renewal every 4 years. In a study conducted in Colombia by Triana et al. (2011), they found that only 21% of the farms renew crops each year. In the case of coffee pulp, this residue is generated in small quantities posing logistical challenges in SCND (Duarte et al., 2016). In all cases, the raw material availability is a relevant issue to guarantee the supply chain feasibility.

Although in the field of biofuel supply chain modeling a large number of contributions is available, there is still space for more investigation. Also, in the particular case of coffee crop residues, mathematical models addressing the BSCND are really scarce. Based on the above, the following research gaps claim for deeper attention:

- The BSCND using multiple coffee crops residues, considering the supply particularities of these raw materials and their effects on strategic and tactical decisions.
- The effect of capacity strategy (expansion and contraction of capacity) on other supply chain decisions such as facility location, transportation and material flows in accordance with demand fluctuation and feedstock constraints.
- In this same line, the effect of capacity strategy on supply chain performance in terms of financial, environmental and social goals providing more realistic analysis to support decision making.
- The integration of location (strategic) and inventory (tactical) decisions into a multi-period problem, to guarantee differentiated material flows toward gathering facilities and biorefineries.
- The economic, environmental and social effects of using multiple coffee crop residues in the context of the BSCND problems.

In order to address the aforementioned gaps, the present study develops a Multiple Objective Mixed Integer Linear Programming model (MOMILP) to design a sustainable supply chain from multiple coffee residues (multiproduct), projecting strategic supply chain decisions in the long term (multi-period). The model proposes a dynamic capacity strategy, analyzing its effects on facility location decisions, transportation and material flows as well as the supply chain performance in terms economic, environmental, and social goals. For its practical validation, the model was used in the bioethanol SCND in Colombia, using coffee stems, pulp, and mucilage.

Based on the obtained results, the main contributions of the present investigation can be summarized as follows:

- To the best of our knowledge, the proposed model is the first that considers the most relevant strategic decisions in BSCND using multiple coffee residues (stems, pulp and mucilage) and their effects on the three sustainability dimensions. From this perspective, logistic implications as well as strategic and tactical decisions involved in bioethanol production using such agricultural residues were evaluated. Decision variables include strategic decisions such as sourcing allocation, capacity strategy, facility location (gathering centers and biorefineries) and differentiated material flows between the supply chain facilities in a multiperiod time horizon.
- Facilities (gathering centers and biorefineries) can be opened, expanded, or closed along the planning horizon. The above implies not only a multi-location solution, but also a dynamic capacity setting. Therefore, this is the first study on BSCND that analyzes the effect of capacity strategy on financial, environmental and social goals. Thus, valuable managerial insights about this decision and its effects on the long-term investments to support decision making are provided.
- Considering the seasonality of coffee residues generation, facility decisions (strategic) are integrated with inventory decisions (tactical) in order to avoid a sub-optimal solution. This model goodness, guarantees proper material flow for each type of residue between facilities, especially considering the supply existing risk of using these biomasses as raw material.
- Environmental performance was assessed considering the BSCND decisions effect on water (total suspended solids) and air (CO_2 emissions) as a consequence of coffee residues utilization. In particular, the positive effect of using this agricultural waste instead of polluting water sources is analyzed. From the social dimension, our model evaluates the impact on job generation; however, unlike most studies, it locates facilities in regions with lower employment rates. Job generation in coffee farms, as a result of waste selling for bioethanol production, was also considered. Finally, to assess the impact on food security, it was assumed that bioethanol production from coffee residues releases a certain amount of land that can be exploited in other cultivations in order to increase food availability for human consumption.

The rest of this paper is organized as follows: in Section 2, the relevant scientific literature is examined. Subsequently, the proposed optimization model is presented in Section 3. Computational results, obtained from a real case in Colombia, are presented in