A decisional simulation-optimization framework for sustainable facility location of a biodiesel plant in Colombia

Yasel Costa, Alexandra Duarte, William Sarache

A R T I C L E   I N F O

Article history:
Received 9 December 2016
Received in revised form 5 August 2017
Accepted 15 August 2017
Available online 23 August 2017

Keywords:
Facility location
Sustainability
Supply chain design
Biofuel

A B S T R A C T

In this paper, we develop a decisional framework and a mathematical model for the sustainable design of biodiesel supply chain networks (BSCND). We consider a broad group of sustainable aims, i.e. standard economic goals (revenue and logistics costs of BSCND), environmental issues based on a biodiesel production life cycle assessment (LCA), and the social incidental aspects (e.g. crime control, political stability, and community attitude, among others). The framework begins with a simulation of the biodiesel production system, feeding later, with suitable input parameters and suitable solutions, and a macro-location model designed to establish the regional positioning of biofuel conversion plants. Optimal regions are used as initial feasible solution space for the proposed micro-location model. In this part of the framework, we introduce an adaptation of Extended Goal Programming to rank the best municipalities (definitive locations) emphasizing the social aspects under consideration. The framework application is set up in the following Colombian context: first generation biodiesel production from palm oil feedstock. Our computational results indicate that the Colombian city of Rionegro (in the Santander region) is the most sustainable location for a new biodiesel plant.

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1. Introduction

Sustainability-oriented research has garnered a great deal of attention in recent years. Especially in the context of supply chain network design (SCND), contributions can be found which address the inclusion of environmental issues (Babazadeh et al., 2017a) and social aspects (Santibañez-Aguilar et al., 2014; Babazadeh et al., 2017b). Undoubtedly, global warming and worldwide environmental issues are common motivations for scientists to join their efforts nowadays. In this sense, biofuel production seems to be one of the most promising alternatives in order to deal with said problems, particularly those of greenhouse gas emissions (Edenhofer et al., 2011) and fossil fuel consumption (Gonela et al., 2015).

The biofuel supply chain network design (BSCND) implies the configuration of a complex material flow that starts with the acquisition of different feedstocks, and ends with distribution of the biofuel produced (Hombach et al., 2016). In the midst of the midstream is one of the hardest decisions in logistic network planning: the facility location of conversion plants (Kocoloski et al., 2011). This issue has been undertaken from different perspectives in the SCND scientific literature. For instance, some authors examine the determination of plant geographical locations based on economic goals (Singh et al., 2014; Cambero et al., 2015). Other contributions analyze, simultaneously, the optimal location and conversion technology to produce biofuel (Marvin et al., 2012a; Sukumara et al., 2014). Furthermore, recent proposals incorporate relevant environmental aspects (Gonela et al., 2015; Duarte et al., 2016) and social criteria (Hombach et al., 2016) in their analyses, when a biorefinery is allocated to a certain feasible region.

Although there many research efforts addressed to biofuel plant location problem using an SCND approach, we believe that there is a dearth of publications which consider the following aspects:

- The biofuel conversion process is mainly treated as a black box, considering most of the parameters involved in this process, such as that of user-defined input data. Also, the integration
between biofuel production system design and the configuration of biofuel supply chain echelons is rarely considered.

- Allocation procedures for biofuel conversion plants have been regional-scope oriented. In some real-life situations, a typical region could have many allocation points, due to the incidence of local-scope factors.
- The inclusion and operationalization of social aspects using optimization models. Analysis of relevant social factors in biorefinery allocation (e.g. the crime control, political stability and community attitude toward plant establishment) is very scarce in the literature.

To address the aforementioned gaps, this paper presents a simulation-optimization framework to support facility location decisions for biofuel plants. The proposed framework can be distinguished from previous studies in the following aspects: firstly, the conversion process parameters and feasible regions for biorefinery allocation are obtained from advanced simulation techniques. Secondly, the simulation outputs and BSCND are integrated into a macro-location model that includes life cycle assessment. Thirdly, particular social aspects are quantified and embedded into a micro-location model, which is a creative adaptation of Extended Goal Programming (EGP).

This paper has been structured as follows. In the next section, relevant scientific literature is examined. Section 3 presents the general structure and the mathematical models included in the proposed framework. Later, the computational results of one realistic case study are discussed in Section 4. Finally, study conclusions and possible future research directions are presented in Section 5.

2. Facility location within the frame of BSCND: a brief literature review

Increasing concern about environmental issues has encouraged the implementation of policies focused on emissions reduction and improvement of the use of vital resources, such as water and soil (Edenhofer et al., 2011). Biofuel production is an alternative approach, in line with the sustainable development of modern society. However, biofuel obtention is just the final state of a very complex, interconnected linkage that involves a number of hard decisions. Due to practical challenges (e.g. the inclusion of environmental and social aspects), many of these decisions can only be addressed through the use of robust mathematical approaches. A good example of the above situation can be seen when supply chain planners (e.g. public planners and industrial practitioners) deal with facility location problems, one of the most difficult decisions of the SCND (see in Marvin et al. (2012b)). The complexity of facility location decisions requires a proper balance between three main performance dimensions: 1) logistics and production costs (economic perspective) (Zhang and Wright, 2014); 2) the environmental impact of operations (ecological perspective) (Guo et al., 2014); and 3) the set of factors affecting community interests (socio-perspective) (Azadi et al., 2015). As shown in Fig. 1, this decision also involves the simultaneous analysis of two non-trivial tasks: the Production System Design (PSD) and the SCND structure.

PSD requires the concurrent analysis of process, capacity and location decisions, in order to establish the most efficient production configuration. In turn, the SCND should consider these logistics costs generated by the material flows. Due to transport operations, this cost mainly depends on network configuration (providers, conversion plants, and customers). Thus, facility location is a strategic decision that should achieve an appropriate balance between production and logistics costs. Therefore, certain aspects related to technology processing, workforce, raw materials, transportation and utility costs, among others, must be addressed in the economic assessment. These costs integrate the so-called quantitative factors which affect facility location decisions.

However, achievement of economic goals is still insufficient for sustainable paradigms. Although cost reduction is very important for facility location problems, environmental and social implications are also relevant (Shabani et al., 2013; Zhang and Hu, 2013). From an environmental point of view, Duarte et al. (2016) establish that carbon and water footprints have been the most analyzed aspects in biofuel-plant location problems. According to Sundarakani et al. (2010) and Çuçek et al. (2012), the environmental effects of a biofuel plant may be analyzed from a quantitative perspective. In regards to social issues, the complexity is increased since this perspective involves so-called qualitative location factors (Vanegas et al., 2008; Cambero and Sowlati, 2016). Therefore, the simultaneous inclusion of qualitative and quantitative factors requires a robust mathematical approach to support decision-making.

The study of quantitative and qualitative factors involved in facility location problems has been a topic of great interest among researchers (Liang and Wang, 1991). Regarding the BSCND, quantitative factors usually comprise production-logistics costs and economic-environmental benefits (Çuçek et al., 2012; Duarte et al., 2014). In addition, qualitative factors include diverse aspects related to weather, utilities, political issues, infrastructure and job creation, among others (Demirel et al., 2010; Dogan, 2012). The level of involvement of these factors depends on three principal elements: the business sector (agricultural, industrial, sales and services), company size (small, medium, large), and the target market (domestic and international) (MacCarthy and Atthirawong, 2003; Mazzarol and Choo, 2003; Sukumara et al., 2014). Based on a comprehensive literature review, 51 factors grouped into eight categories have been identified (depicted in Fig. 2). Although cost is the most important category affecting facility location decisions, a wide set of qualitative factors must be also considered. This result is coherent with the findings of Melo et al. (2009).

Based on the above, the simultaneous inclusion of qualitative and quantitative factors in a sustainable context (i.e. the proper
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