Chemical Engineering Science 93 (2013) 429–444

Contents lists available at SciVerse ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

# Sustainable distributed biodiesel manufacturing under uncertainty: An interval-parameter-programming-based approach

Zheng Liu, Yinlun Huang*

*Department of Chemical Engineering and Materials Science, Wayne State University, Detroit, MI 48202, United States*

HIGHLIGHTS

- An interval-parameter-programming-based strategic planning method is introduced.
- It can be used to investigate systematically manufacturing sustainability problems.
- Uncertainty in strategic planning is handled and optimal strategy can be identified.
- A sophisticated biodiesel manufacturing study demonstrated methodological efficacy.

ARTICLE INFO

*Article history:*
Received 8 August 2012
Received in revised form
31 January 2013
Accepted 8 February 2013
Available online 24 February 2013

*Keywords:*
Sustainability
Bioprocessing
Systems engineering
Optimization
Simulation
Uncertainty

ABSTRACT

Biodiesel, a clean-burning alternative fuel, can be produced using different types of feedstock and processing technologies. However, how to strategically plan for sustainable biodiesel manufacturing in large geographical region is very challenging, mainly because of technical/non-technical complexity, economic, various environmental and social concerns, and data and information uncertainty. In this paper, we introduce an interval-parameter-programming (IPP)-based strategic planning methodology. By this methodology, the sustainability performance of biodiesel manufacturing technologies and processes can be assessed systematically, and the IPP-based optimization can then generate optimal strategies for sustainable distributed biodiesel manufacturing under uncertainty. The efficacy of the introduced methodology is demonstrated by a sophisticated case study.



## 1. Introduction

Biodiesel, a clean-burning alternative fuel, can be manufactured by the transesterification of different types of feedstock (e.g., vegetable oil and animal fats) with alcohol (e.g., methanol or ethanol). A variety of biodiesel manufacturing technologies have been developed, such as those alkali or acid catalyzed, and non-catalyzed under supercritical condition (Zhang et al., 2003a; West et al., 2008; Apostolakou et al., 2009; Glisic and Skala, 2009; Santana et al., 2010). Technology adoption is mainly based on feedstock availability, fuel demand, manufacturing cost, transportation cost, regulations, etc. In the past decade, about 200 biodiesel plants were built in more than 40 states in the U.S., with a total annual manufacturing capacity of about 10 million tons (Biodiesel Magazine (BM), 2012). Nevertheless, a recent survey shows that many biodiesel plants in different regions are either in idle mode or operated below design capacity, because the production could not be economically justified (American Soybean Association (ASA), 2012). On the other hand, tens of new plants are under construction in many other regions due to resource availability, fuel demand increment, economic development, etc (Biodiesel Magazine (BM), 2012). It is predicted that national biodiesel manufacturing capacity needs to be continuously increased. Apparently, biodiesel production must be carefully planned in order to ensure manufacturing sustainability.

Strategic planning for sustainable biodiesel manufacturing is mainly about the selection of appropriate manufacturing technologies and the development of distributed production strategies when regional feedstock availability and biodiesel demand are known. Among these, sustainability assessment of biodiesel manufacturing technologies is a critical task. Zhang et al. (2003b) and You et al. (2008) conducted detailed economic evaluations of several technologies. Othman et al. (2010) introduced a modular-based assessment approach for sustainable process design, which was used to compare two biodiesel processes (alkali-catalyzed versus non-catalyzed with supercritical methanol). In their approach, the net annual profit and the discounted cash flow rate of return were used to assess

* Corresponding author. Tel.: +1 313 577 3771; fax: +1 313 577 3810.
*E-mail address:* yhuang@wayne.edu (Y. Huang).

0009-2509/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.ces.2013.02.024

economic sustainability, the EPA's potential environmental impact (PEI) evaluation method (Young and Cabezas, 1999) was adopted to evaluate environmental sustainability, and a number of "soft" indicators, such as safety, operability, and local demand satisfaction, were utilized to assess social sustainability. Li et al. (2011) extended the approach of Othman et al. (2010) by incorporating exergy analysis (Yi et al., 2004; Baral and Bakshi, 2010a, 2010b) and inherent safety analysis (Heikkilä, 1999) into the assessment of two alkali-catalyzed biodiesel processes. Note that in those known studies, the information uncertainty associated with feedstock availability, regional product demands, transportation, etc., was not considered in sustainability assessment and decision-making.

Uncertainties can be, in general, classified into two categories: the aleatory and the epistemic uncertainties (Parry, 1996). The aleatory uncertainty is referred to the variations associated with physical systems and/or the environment; it is objective and irreversible. By contrast, the epistemic uncertainty is carried due to a lack of knowledge and/or information; it is subjective and reducible. The uncertainties encountered in strategic planning can be either aleatory or epistemic.

A variety of uncertainty handling methods are available, such as those by resorting to statistical theory, fuzzy set theory, and artificial intelligence. For instance, probability bounds analysis (PBA) (Tucker and Ferson, 2003) expresses uncertainty using a probability-box (or p-box) approach (Moore, 1966; Walley, 1991; Ferson et al., 2003), where a p-box represents a range of distribution functions. Since the availability of distribution functions is a requirement and uncertainty propagation modeling is a major challenge, PBA-based methods become not suitable in the study of many types of strategic planning problems. Fuzzy logic and fuzzy programming based approaches are attractive in formulating and manipulating epistemic uncertainties, where rigorous logics are used to deal with fuzzy information that is difficult to compute using conventional mathematical methods (Piluso et al., 2010). Its solution derivation is usually transparent. However, decision quality is largely affected by the definition of fuzzy sets or fuzzy numbers, where subjective judgments are used to a large extent due to data scarcity. Information gap theory (IGT) (Ben-Haim, 2006) is a fairly new method for expressing uncertainty and making decisions when only the best guess of a specific quantity is available (Ben-Haim, 2005; Hine and Hall, 2010). The information gap is defined as a disparity between what is known and what needs to be known in order to make a responsible decision. However, the mathematical framework of IGT looked to be complicated to use in modeling decision-making problems (Gelman, 2009).

Interval-parameter-based uncertainty handling is an interesting approach, by which parameter uncertainties are expressed using interval numbers, and there is no requirement on data distribution information (Xia et al., 1997). This type of approaches should be suitable for the study of various sustainability assessment and decision-making problems, where probability functions are not derivable from accessible data. This is particularly true for strategic planning, since the accessible data are usually limited and uncertain, and the parameter value ranges are known, but data distribution information is unavailable (Piluso and Huang, 2009).

In this paper, we introduce an interval-parameter-programming (IPP)-based strategic planning methodology. By this methodology, sustainability assessment of biodiesel manufacturing technologies is formulated as an integral part of a decision making framework. The IPP-based optimization is used to derive optimal strategies for distributed biodiesel manufacturing in a large geographical region under a variety of uncertainties. The remainder of the paper is organized as follows. First, we define the scope and objective of strategic planning for sustainable regional biodiesel manufacturing. Second, a general definition of an interval number and an arithmetic operation method are introduced for uncertainty handling. Subsequently, a set of interval-parameter-based formulations are proposed for sustainability assessment. After these, an IPP-based optimization method is introduced, where an approach for incorporating sustainability performance of biodiesel manufacturing technologies is explained, and a solution identification procedure is described. The efficacy of the introduced methodology will be illustrated through investigating a sophisticated distributed biodiesel manufacturing problem.

## 2. Planning for sustainable manufacturing—tasks and data processing

A strategic plan for distributed biodiesel manufacturing in a large geographical region is acceptable only if it can show that its implementation should ensure manufacturing sustainability over the full life cycle of the manufacturing facilities. Thus, it is required to determine carefully which technologies should be used, how many plants should be built and where, what the production capacity of each plant should be, and how to measure manufacturing sustainability. The development of a strategic plan involves three major tasks: (i) data gathering and processing, (ii) sustainability assessment of manufacturing technologies, and (iii) decision making for strategy development. Fig. 1 depicts a general approach for strategic plan development.

### 2.1. Data gathering and processing

The data needed for strategic planning can be divided into two categories: the technical and the non-technical ones. The data can be obtained from different sources and through system simulation. Note that many data can be uncertain, and thus should be carefully handled.

The technical data are mainly those related to manufacturing processes using different biodiesel manufacturing technologies, such as those about raw materials, energy consumption, waste reduction and waste handling, plant capital and operating costs, product quality and production rate, etc. The data can be generated through simulating candidate processes that are designed using different types of feedstock. The process data from computer simulation using state-of-the-art simulators do not contain significant uncertainties. For each type of process, simulation should be conducted at different

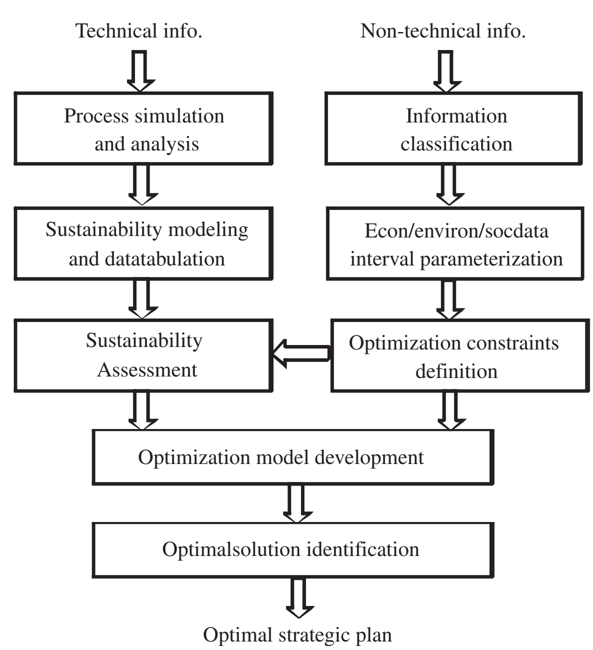


**Fig. 1.** Tasks and general approach for strategic planning.