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Robust optimization on sustainable biodiesel supply chain produced from waste cooking oil under price uncertainty

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ABSTRACT

Waste cooking oil (WCO)-for-biodiesel conversion is regarded as the "waste-to-wealthy" industry. This paper addresses the design of a WCO-for-biodiesel supply chain at both strategic and tactical levels. The supply chain of this problem is studied, which is based on a typical mode of the waste collection (from restaurants' kitchen) and conversion in the cities. The supply chain comprises three stakeholders: WCO supplier, integrated bio-refinery and demand zone. Three key problems should be addressed for the optimal design of the supply chain: (1) the number, sizes and locations of bio-refinery; (2) the sites and amount of WCO collected; (3) the transportation plans of WCO and biodiesel. A robust mixed integer linear model with muti-objective (economic, environmental and social objectives) is proposed for these problems. Finally, a large-scale practical case study is adopted based on Suzhou, a city in the east of China, to verify the proposed models.

1. Introduction

WCO-for-biodiesel conversion is regarded as a helpful means to cope with food safety, energy crisis and environmental problems. It's estimated that China has produced considerable amount of WCO annually (about 4–8 million tons), and half of them could be collected for recycling. However, WCO is not satisfactorily recycled for industry use in the past years, as 40–60 percent is backflow to dining tables through various channels (Zhang et al., 2014), and the rest is mostly disposed as rubbish.

For this regard, China government has highly supported the WCO-for-biodiesel industry and proposed that WCO should be the main feedstock of biodiesel in the document "Biodiesel industry development policy" (2015). However, lots of biorefineries still go out of business due to various obstacles where WCO supply and biodiesel sales are the two major bottlenecks: (a) WCO is produced daily by numerous entities (such as restaurants, hotels, and households) who scatter all over the city, and each of them just accounts for a minor proportion. So it's costly to go over the whole city for WCO collection. (b) It's more profitable to producing edible oil than biodiesel, thus a large amount of WCO is illegally collected and backflow to dining tables by small vendors. So it forces biodiesel producers to pay more for purchasing WCO, otherwise they have to sult down due to feedstock shortage. (c) Although biodiesel proves to be very similar to conventional diesel on physical properties (Bozbas, 2008), there is still a low public acceptance of biodiesel in China. Especially, the three largest fuel suppliers in China haven't added biodiesel into fossil fuel for sales, thus most of biodiesel has to been sold with a low profit and great demand uncertainty to private gas stations or construction firms.

In a word, WCO-for-biodiesel industry is suffering from the pressure of supply and demand shortage, thus it's an urgent call to take the two aspects from the view of supply chain optimization. In another word, there should be a professional WCO recycling logistics system (Zhang et al., 2012), an efficient biodiesel sales network as well as a robust ability to overcome the uncertainties. Therefore, this paper tries to address the robust optimization of a WCO-for-biodiesel mode in the city under uncertainties.

2. Literature review

From the view of feedstock and product aspects, WCO-for-biodiesel supply chain was not only a waste recycling supply chain but also a biodiesel supply chain. Similar to other biomass-for-biofuel supply chains, it should be divided into upstream, midstream and downstream segments (Meyer et al., 2014), and they were namely WCO collection, biodiesel production and biodiesel sales system.

WCO collection system was always considered as a main bottleneck and treated by referring to the waste recycling process. Zhang et al. (2012) designed a structured questionnaire to survey 246

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restaurants in Nanjing, China and recommended that a perfect recycling service network should be established firstly to reuse WCO. In order to explore the suitable WCO recycling modes, Zhang et al. (2014, 2015) and reviewed the current modes (namely Suzhou, Nanjing, Ningbo and Lanzhou mode) in China and made a good comparison with US and Japan, finally they found Suzhou and Ningbo modes may perform better than others. Vehicle routing problem was also a challenge as WCO is scattered in the cities. Ramos et al. (2013) introduced the capacity and duration constraints into this problem and applied it to a real WCO collection system which consists of 188 restaurants, 80 schools and 35 canteens.

Biodiesel production and sales system was more similar to a biofuel supply chain, which had gained wide attention in recent years. The most important reason for adopting biofuel was to increase energy security, sustainability as well as to deliver competitive lower cost products to the end-user market (Awudu and Zhang, 2012). Thus the economic, environmental and social aspects should be analyzed firstly to prove whether to produce biodiesel form WCO or not. Until now, most literatures had proved WCO to be a promising feedstock to produce biodiesel for the feasibility on fossil fuel substitution (Tsai et al., 2007; Sheinbaum-Pardo et al., 2013; Liang et al., 2012), emission reduction (Peiró et al., 2010; Dufour and Iribarren, 2012), as well as advantages of decentralized production (Iglesias et al., 2012; Kelloway et al., 2013). The supply chain problem was one of the most important bottlenecks that limits the promotion of biofuel (Zhang et al., 2012). It had been studied for various feedstock (lingocellulosic, agriculture residues, forest biomass, etc.) on strategic, tactical and operational level, involving decisions on facility location, transportation plan, technology selection, inventory management, vehicle dispatch and so on. These literatures had been well reviewed by Sharma et al. (2013), Meyer et al. (2014) and Yue et al. (2014). However, to our knowledge, there was no study had specially designed the whole WCO-for-biodiesel supply chain.

Unlike other supply chains, there were higher level of uncertainties in biofuel supply chain (An et al., 2011; Kim et al., 2011). Lots of studies had optimize the supply chain under different uncertainties to achieve better economic (namely cost minimization, net supply chain value or profit maximization) and environmental objectives (namely emission reduction or energy saving). These uncertainties mainly included biomass supply, transportation and logistics, production and operation, demand and price as well as policy uncertainties, as discussed by Awudu and Zhang (2012). Until now, most of studies dealt with the uncertainties via stochastic optimization (Giarola et al., 2011; Chen and Fan, 2012; Shabani and Sowlati, 2013; Osmani and Zhang, 2013, 2014; Li and Hu, 2014), fuzzy optimization (Balaman and Selim, 2014), as well as robust optimization (Mansoornejad et al., 2013; Foo et al., 2013; Tong et al., 2014). As for the uncertainties for WCOs-for-biodiesel supply chain, Jiang et al. (2014) analyzed the WCO collection, biofuel production, biofuel sales, logistics as well as government policies and industry regulations process, and concluded that the WCO collection uncertainty is more complex than other biofuel supply chains due to its numerous and scattered suppliers.

As aforementioned, it's still meaningful and a lack to construct a robust WCO-for-biodiesel supply chain under uncertainties when economic, environmental and social objectives are considered, and this paper aims to optimize its WCO collection, biodiesel production as well as biodiesel sales process at both strategic and tactical level.

3. Problem statement

3.1. Assumptions and notations

This paper considers a three-level WCO-for-biodiesel supply chain and its process is illustrated in Fig. 1. In such a supply chain, there are three major stakeholders: WCO supplier, integrated bio-refinery as well as demand zone, and its process can be simply explained as follows (Jiang and Zhang, 2016): kitchen waste is produced daily at supplier sites (restaurants, hotels, agro-food industry etc.). After that, it's collected by small trucks and transported to integrated bio-refineries for pretreatment and biodiesel conversion. The produced biodiesel is finally delivered to the demand areas (gas stations, construction enterprises, etc.).

For in-depth analysis, this paper partitions the supply chain into three subsystems, which are WCO collection, biodiesel production as well as biodiesel sales system. Suzhou mode is a typical mode for WCO collection and conversion in the cities, which has been well studied by Zhang et al. (2014). WCO suppliers and collectors are the two stakeholders. WCO suppliers scatter all over the city and produce considerable WCO daily. WCO collectors can be individuals or enterprises who have several vehicles, and they are always a part of bio-refineries or employed by them. Generally

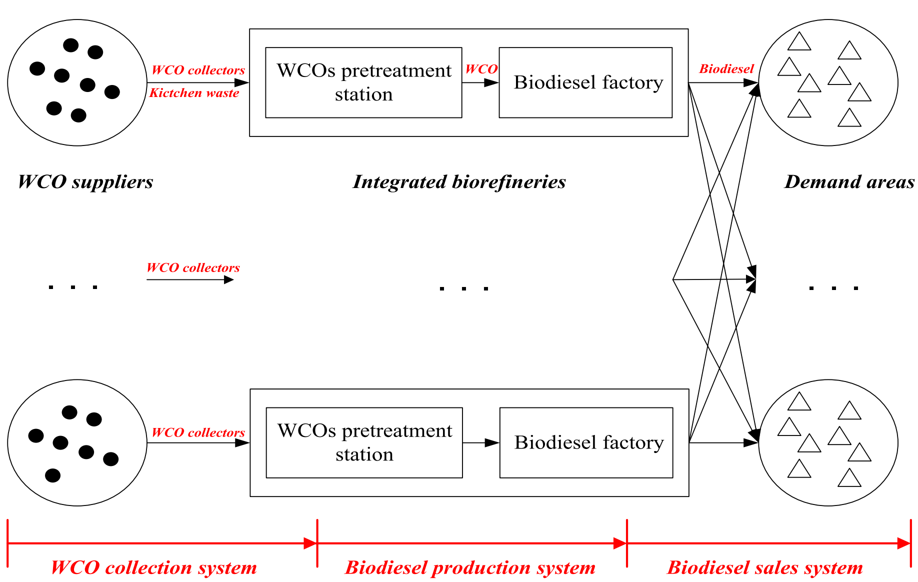

Fig. 1. Illustration of the WCO-for-biodiesel supply chain.

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