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A location-inventory-routing optimization model for cost effective design of microalgae biofuel distribution system: A case study in Iran

Farhad Habibi[a], Ehsan Asadi[a,b], Seyed Jafar Sadjadi[a,*]

[a] Department of Industrial Engineering, Iran University of Science and Technology, Tehran, Iran
[b] Chair of Air Transport Technology and Logistics, Technische Universität Dresden, Dresden, Germany

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ABSTRACT

This paper presents a Location-Inventory-Routing Problem (LIRP) optimization model for designing an algae fuel production and distribution network consisting of biomass production facility, distribution facilities, and extraction sites. The proposed model minimizes the total cost of the network including the cost of locating the distribution facilities and transportation and the expected inventory costs including holding, shortage, ordering and purchase. The proposed model helps decision-maker determine the optimal location and order policy of algae fuel distribution facilities, allocation of extraction sites to these facilities, and the routing decisions. The proposed model falls within the category of NP-hard problems and is solved with the modified versions of three algorithms; namely Simulated Annealing (SA), Genetic Algorithm (GA) and Firefly Algorithm (FA), and the performance of these methods are measured by test problems in different sizes. The results show that SA outperforms both GA and FA, and GA outperforms FA in terms of the quality of the solutions. Finally, the proposed model is validated and evaluated by a case study of algae fuel distribution network in Iran and the results are discussed.

1. Introduction

The major sources of environmental pollution including energy, transportation and agriculture sectors, which in Europe for example, account for 60%, 20%, and 9% of total greenhouse gas emissions, respectively. With the steady growth of developing economies, global energy consumption is expected to increase progressively, and this increased consumption is expected to result in further damage to the environment [1–3]. At present, the main sources of energy are fossil fuels such as oil, coal and natural gas, which given the current rate of consumption, are expected to deplete before the end of present century. In addition, substantial environmental impacts of these energy sources, including global warming, acid rains, and heavy air pollution in major cities, highlight the need for environmentally sound alternative energy sources [4]. Despite the marginal attention given to biomass because of the issues such as variations in biomass availability, high moisture content, low bulk density and dispersed distribution of biomass [5], production of biofuels, bioenergy and chemical intermediates from biomass are still considered as a viable environmentally-friendly strategy [6]. Depending on the raw materials to be used in process, bioenergy technology is categorized into four generations. In the first generation, energy is produced from the crops such as corn and soybean, which is cost-effective but naturally leads to increased food prices because of land competition [7]. In the second generation, energy is produced from lignocellulosic biomass, which circumvents the issue of land completion [8] but requires complex processing [9]. Meanwhile, the use of algae as biomass allows CO_2 emission to be removed from production process without encountering the issues of the first and the second generations. When utilized on the same scale, algae biomass provides greater efficiency than other generations of bioenergy. In addition, algae must be cultivated in artificial ponds, and this prevents the problem of land competition. Another merit of algae is its ability to sustain and produce huge amounts of oil and to grow in saline and sewage water [10]. Algae-based bioenergy generation systems are divided into two classes, photobioreactor and open ponds, each with its own advantages and drawbacks. The notable advantages of open ponds include easier cleaning, low energy input levels, and easier maintenance, while photobioreactors enjoy some advantages such as higher production yield, easier sterilization, and lower energy consumption [11]. There are two methods of algae fuel production: continuous and batch. Given the advantages of continuous production such as greater control and better system analysis opportunities, this method of production is generally recommended over batch production [12].

Existence of some features in the production and distribution system

* Corresponding author. Department of Industrial Engineering, Iran University of Science and Technology, Narmak, Tehran, 16846-13114, Iran.
E-mail address: sjsadjadi@iust.ac.ir (S.J. Sadjadi).

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of biofuels (such as biomass from algae) can be attributed to the importance of modeling the supply chain for this system. Seasonal variability of biomass production, spatial fragmentation of biomass resources and year round demand for transportation fuel are the examples of these features which make modeling algae biomass supply chain significant [13]. Because of these characteristics, employing the traditional approach is not acceptable. Therefore, utilizing a supply chain modeling and optimization approach not only handles these issues, but also ensures that all activities, from the first section (produce) to the last section (consume), are carried out efficiently [14]. On the other hand, in today's business environment, designing an efficient supply chain plays an important role for coordination between the different parts of a production and distribution network and reducing distribution systems costs. Therefore, there are some researches, which consider designing the production and distribution network of algae biomass supply chain.

Ahn et al. [15] proposed a deterministic mathematical model to design a microalgae biomass-to-biodiesel supply chain network. The model determines the location of bio-refineries and allocation of feedstock to end users, which bring about a cost efficient model. They validated their model in South Korea. Mañalac and Ubando [16] studied an optimization model for distribution system of microalgae biodiesel from production site to local oil depot's scattered throughout the Philippine city, which considered the CO_2 emission and cost as the main objectives to find the efficient routes for microalgae biodiesel transportation. Using a supply chain optimization approach and proposing a multi-scale multi-period mixed-integer nonlinear programming (MINLP) model, Yue et al. [17] considered a model for designing CO_2 transportation pipeline network, selecting algae processing route and product, as well as the seasonality in CO_2 source availability and algal biomass productivity. Their model is also able to optimize cost and CO_2 emission simultaneously by determining number, location, and size of bio-refineries. Mohseni and Pishvaee [13] considered a microalgae-based biofuel supply chain network and to tackle with uncertainty and proposed a robust optimization method. Mohseni et al. [18] also designed and planned a microalgae-based biofuel supply chain network by using a two-stage optimization model. In this model, in the first stage, potential locations for bio-refineries were found by GIS and Analytical Hierarchy Process (AHP) and in the second stage, location and allocation variables were determined by solving a robust mixed-integer linear programming (RMILP) optimization model. Wu et al. [19] developed an MINLP model for minimizing GHG emission life cycle in microalgae-based energy system. After optimizing the heat exchanger network and maximizing the heat recovery, this model optimizes the algae biofuel production chain. Their investigation shows the efficiency of the model for minimizing GHG emissions.

Incorporation of distribution schemes into supply chain problems and decisions often results in reduced overall system costs. Accordingly, designing an integrated and efficient dedicated supply chain may contribute to successful implementation of algae fuel distribution network. For a distribution network to be designed properly, three problems of inventory control, location-allocation, and routing must be properly considered. Simultaneous formulation of these three aspects in the distribution network design problem can improve the prospect of success in achieving distribution network objectives [20] [21]. This is while the majority of studies in the field of integrated distribution networks have been focused on two of the three mentioned aspects, or namely inventory-routing problem (IRP), location-inventory problem (LIP) or location-routing problem (LRP). The notable examples of research on these problems include, but not limited, to the studies of Federgruen and Simchi-Levi [22], and Cordeau et al. [23] on IRPs, the works of Shen [24], Erlebacher and Meller [25], and Daskin et al. [26] on LIPs, and the studies of Boventer [27], Assad [28], Nagy and Salhi [29] and Wu et al. [30] on LRPs.

In addition to integration, other approaches to combination of complex inventory systems have also been studied. For example, the use of queue network and multi-echelon inventory models to relate the processes of production, service, and inventory management can provide a broader and more practical perspective than traditional models [31–33]. One of the earliest works with this approach is the study of Sigman and Simchi-Levi [34], where a light traffic heuristic method was developed for an M/G/1 queue system with limited inventory. Later, Berman and Kim [35] introduced a dynamic replenishment problem with Markov decision formulation. The aim of their study was to determine the replenishment policy that would optimize the customer satisfaction as well as the cost of ordering, inventory holding and replenishment. Schwarz et al. [31] studied several systems of M/M/1 queue with single server and attached inventory, where demands received during out-of-stock times were considered to be lost. Teimoury et al. [36] proposed a production-inventory-queue model where demands and leadtimes were non-deterministic. They also developed an efficient computational algorithm to solve this model, and implemented the resulted model for a case study. Saffari et al. [32] introduced a system of M/M/1 queue with inventory where demands and lead times were non-deterministic and had Poisson and exponential distributions, respectively. Baek and Moon [37] also used the M/M/1 queue to develop a production-inventory model where demand had a Poisson distribution while lead-time followed an exponential distribution.

In summary, due to the importance of designing an efficient supply chain network for algae biomass production and distribution system and also considering three aspects of location-allocation, inventory policies and routing decisions simultaneously, a mixed integer nonlinear optimization model is presented in this paper to fill the following gaps in the literature:

- The continuous review policy requires constant awareness of inventory levels. If customer demand is one unit, then the order size (Q) will always be $S - s$. Thus, (s, S) policy will turn into well-known continuous review policy (r, Q) where $r = s$ is the reorder point. When ordering cost of (r, Q) policy is negligible, it is called one-for-one, ($S - 1$, S) or base stock policy [38,39]. Thus, unlike the previous studies which use the (r, Q) system, in this paper, inventory system of algae fuel distribution network follows the ($S - 1$, S) policy.
- As mentioned in the review of studies on supply chain problems, designing the distribution system within the supply chain framework leads to significant reductions in overall system costs. The literature on distribution system of renewable fuels such as biomass is quite scarce. Thus, there is a need for further work on integrated algae fuel distribution networks where location-routing-inventory decisions could be considered at the same time.
- Since routing and location problems are both NP-hard [24,40], their combination (LRP) is also an NP-hard problem, and so will be the LRIP, which can be considered a more general form of these problems. Therefore, in this paper, the proposed model is solved by modified versions of three algorithms SA, GA and FA and the obtained results are compared with each other.
- To validate the developed model, the paper also presents the results of a case study on algae fuel distribution network in Iran.

This paper is organized as follows. In this section, the subject of the study was explained and the literature on the subject and the similar models were reviewed. In the rest of the paper, Section 2 describes the framework and the overall structure is considered for algae fuel production and distribution system and the corresponding model. Section 3 describes the problem-solving approaches. In section 4, the meta-heuristic algorithms used for solution and their results are compared. Section 5 explains the way the model is used to design an algae fuel production and distribution network in Iran, and presents the results of this case study. In the final section, we summarize the results of the study and recommend some directions for future research.