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MATHEMATICAL OPTIMIZATION OF MACROALGAE-BASED BIOFUEL SUPPLY CHAIN – A LOGISTIC CASE STUDY IN KOREA

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ABSTRACT

Due to depleting fossil fuels, finding new and renewable energy resources becomes a strategic issue for the world. Although macroalgae has indigenous attractive, it does not play a key role in substitution for fossil fuels. Therefore, this work addresses the optimal design of macroalgae- based biofuel supply chain under economic objective to determine strategic level decision. It proposed mixed integer linear programing (MILP). the objective is minimizing total annual cost with regards to meet the fuel demand.

Applicability of the proposed mathematical model is illustrated through a case study of south Korea. It is located in east Asia that is home of macroalgae.

Keywords: macroalgae-to-biofuel conversion, biofuel supply chain, mixed integer linear programing (MILP), sustainability, strategic decision

1. INTRODUCTION

Based on International Energy Outlook 2016, energy consumption in transportation sector at an annual average rate of 1.4% will grow from 104 quadrillion Btu in 2012 to 155 quadrillion Btu in 2040[1]. The road transport Considering almost depends on petroleum derived fuels, reducing fossil fuels dependency it may represent not merely a strategic decision, but an environmental imperative.

Biofuels have played an important role in the search for alternatives as they have seemed the only acceptable approach to replace for petroleum-based traditional fuels in the transport sector[1]. Bioethanol is one type of biofuel that can be substitute for gasoline.

Procurement and use of feedstocks (biomass) for producing bioethanol and its delivery to end use is called biofuel supply chain network. Since the economics of biorefinery is heavily dependent on feedstock cost, the efficiency of this chain is critical: as the biomass itself is rather not expensive, the price of biomass carried to the biorefinery is significant fraction of logistic cost. The main objective of supply chain management in this paper is to optimize strategic decisions for the managing of supply chains[2].

biofuel supply chain management studies have largely been considered the first-generation biofuels (e.g. bioethanol), which are produced from food crops, or the second-generation biofuels obtained from cellulosic[2]. However, producing biofuel from these resources is accompanied by problems such as arable land competition and subsequent surge in food prices[3]. To dominant such problems, investigators have focused on third generation biofuels made from marine biomass (microalgae and macroalgae) due to following reasons: (1) no land requirement for cultivation; (2) indigenous faster growth rates; (3) ability to use seawater and sewage to produce biomass; (4) relatively few nonproductive parts such as roots or stems;(4) higher carbohydrate content suitable for biochemical conversion; [4].

Compared to microalgae, macroalgae have several advantages; they are easier to harvest and generating more net energy since they are multicellular[5]. However, there have been few investigations focused on macroalgae-based biofuel supply chain. Although there are several studies on possibility of macroalgae as a biomass feedstock for biofuel [5], to the best of our knowledge, this study is the first study proposing the biofuel supply chain model based on macroalgae as a feedstock. Because this feedstock is mainly produced in Asia, this makes macroalgae a good candidate for biomass feedstock in Asian countries. For example, Korea exported US $67 million worth of macroalgae to the United States in 2017[6]. Due to the reasons mentioned above, in this study we developed a mathematical model for the strategic planning of macroalgae-based biofuel supply chain.

2. MACROALGAE-BASED BIOETHANOL SUPPLY CHAIN NETWORK

This paper deals with the strategic design and planning of macroalgae-based bioethanol supply chain network (MBBSCN) in multiple periods. The structure includes nodes that refer to harvesting sites and demand zones as well as technologies used (biomass and biofuel storage, dryer and biorefinery) in MBBSCN. The time horizon is decomposed into a finite number of time periods. In the remainder of the paper the time horizon is one year and the time period is fixed to one month to be coherent with the data.

At harvesting sites, available amount of biomass is given for each site and each time period and the amount of harvesting is considered as a decision variable. Besides, the percentage loss in shipping and price of biomass are known in each time period. The biomass feedstock freshly harvested contains considerable amount of water approximately 85% by weight. Thus, it weighs more and has a larger volume before drying. Therefore, shipping the dried one is more economical. Furthermore, a drying process is often needed to convert biomass into a stable form in order to increase its shelf-life and reduce transportation cost[7]. Hence, feedstock is shipped from a harvesting site to a dryer directly. The location of dryer can be optimized by the optimization model. To increase the operational flexibility of MBBSCN, there is no constraint set to affect the potential location of a dryer. It should be also noticed that dryers have different technologies and can have different levels of capacity. Therefore, in order to propose a capable model for MBBSCN, there is possibility to use dryers with different technology and capacity with respect to the amount of feedstock.

The extra dried macroalgae and bioethanol are stored to biomass and biofuel storage, respectively. For increasing efficiency of MBBSCN different levels of capacity of storage are considered. Besides, deterioration rate of dried seaweed during storage in each time period is given.

, the costs of conversion technology for each potential Biorefinery at different capacity levels are given. The process of biorefinery is very complicated; however, to simplify the model and decrease time of calculation, we have modified equations developed in [8]. Finally, the biofuel demand in each time period for each demand zone is given.

The objective function is the total annual cost of MBBSCN. The major decision variables including following:

- Amount and schedule of Feedstock harvesting at each harvesting site
- Number, size and location of technologies
- Amount of feedstock stored in biomass storage and used in biorefineries
- Ethanol yield and amount of ethanol stored in biofuel storage

3. *MBBSCN MODELLING*

The mathematical model of MBBSCN is formulated as a mixed-integer linear programming (MILP) problem consisting of equality and inequality constraints and an objective function. A mathematical planning model is developed for designing a strategic biofuel supply chain from macroalgae harvesting sites to demand zones, while simultaneously improving resource satisfaction, technologies, and demand constraints during planning horizon.

The objective function of the concerned biofuel supply chain is total costs. Which is given in the equation below:

$$COST = C^{FX} + C^{OM} + C^{D} + C^{MS} + C^{FS} + C^{BTRS} + C^{ETRS} + C^{IM}$$

where C^{FX} and C^{OM} are is capital cost of biorefinery and operation and maintenance cost of biorefinery, respectively. C^{D}, C^{MS}, C^{FS}, C^{BTRS}, C^{ETRS}, and C^{IM} are total cost of dryer, cost of biomass storage, cost of biofuel storage, cost of biomass transport, cost of biofuel transport, and total cost of biofuel import, respectively.

4. *CASE STUDY*

Applicability and robustness of the proposed model are illustrated by using a real case study from South Korea. The aquacultured species considered is seaweed that cultivated in south east Asia and accounting 99.6 present by quantity. *Saccharina* is one of these species produced in China(88.3%), South Korea(6.6%) and North Korea (4.4%)[9]. In this study *Saccharina japonica* is used as biomass feedstock. We consider 12 time periods per year (one month as one time period) to investigate the effect of seasonality on supply chain. South Korea has 15 provinces and major cities. Each province/city is taken into account as a harvesting site as well as a potential location for facilities and demand zones. In this study we consider 5% of current gasoline usage met by ethanol (E5). The available amount of feedstock and demand in each province is given in Figs 1 and 2, respectively.

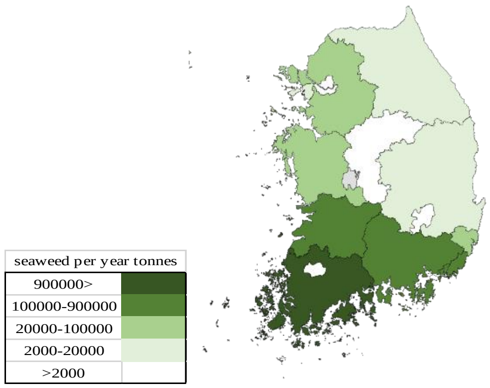

Fig 1 Spatial distribution of biomass resources

Among biochemical conversion routes fermentation is considered for biorefinery technology. To increase flexibility of the model, we consider five levels of ethanol production capacity based on the available amount biomass that can be harvested, with capacities ranges of 0–7.5 million gallons per year (MGY), 7.5–15.5 MGY, 15.5-23 MGY, 23–31 MGY and 31– 38 MGY. The design and cost estimates are based on the superstructure developed in [6]. The technology used to achieve the moisture content 15% of feedstock(dry biomass) from raw seaweed with a moisture content of 85% (wet biomass) is bed drying, which used for biofuel supply chain in [10] and the capacity is varied between to 93,000 dry tonnes per year.

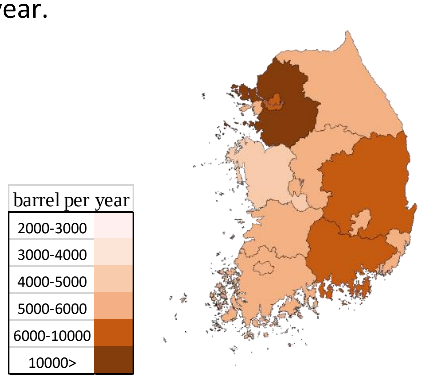

Fig 2 An indicative map of biofuel demands.

5. *RESULTS*

The resulting problem has 180 binary variables, 59,700 integer variables, and 81,804 continuous variables. Models and solution procedures are coded in GAMS software on a PC with Intel®Core™ i7-5960X CPU @ 3.00 GHz and 128 GB RAM, running Window 7 operating system. Furthermore, the MILP problems are solved using CPLEX 12.7.

The best-known minimum annualized cost for the province-level supply chain is $654,718,146. The facilities including in this supply chain are biomass storage, dryer, biorefinery and biofuel storage. The amount of seaweed harvested in south Korea is enough to meet the 90 percent of demand of all provinces. Therefore, building biofuel storage is not necessary. Since a seaweed farm is placed in coastal regions, all coastal provinces have macroalgae farms.

As described earlier in Section 2, wet biomass and dry biomass have different characteristics; the wet biomass is heavier than dried biomass because of the difference in water content. Thus, the transportation of wet biomass costs more. Consequently, dryers should be located near seaweed farms and each coastal province has dryers. It should be noticed that the technology used for drying is bed drying[3] with different capacity is considered in MBBSCN. Among the Korean provinces Jeollanam-do has the most amount of seaweed. Thus, the biggest dryer is built in that province.

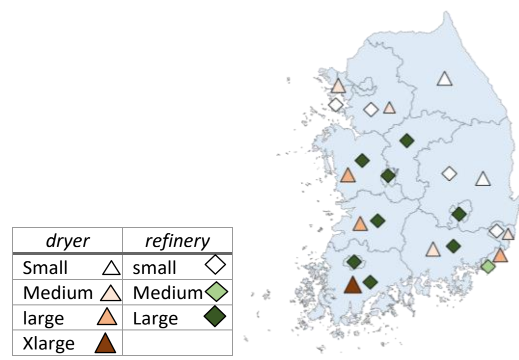

Fig 3 Optimal design of macroalgae-based biofuel supply chain network of South Korea

There are two important points in selecting and managing biorefineries: (1) these facilities has limitation in producing biofuel; (2) the cost of transferring biofuel is more expensive than transferring biomass. In order to overcome the first issue, some provinces that have large amount of seaweed can send extra feedstock to biorefinery in another province. For instance, Jeollanam-do transports dry biomass to eight provinces and cities. The solution for second issue is to build biorefineries that near demand zone and harvesting site. Fig 3 shows the optimal solution for the location of facilities (dryers and biorefineries) and the capacity of facilities mentioned in Table 1. As shown in the figure, the west provinces that have larger amount of seaweed produced have the largest biorefineries and east and north east provinces and cities have biorefineries with smaller capacity.

Table 1 Capacity of technologies

technology	Maximum Capacity
Small biorefinery	7.5MGY
Medium biorefinery	15.5MGY
Large biorefinery	38MGY
Small dryer	325 dry tons per year
Medium dryer	2,602 dry tons per year
Large dryer	20,817 dry tons per year
XLarge dryer	1,332,308 dry tons per year

6. *CONCLUSION*

In this article, we have developed an optimization approach for design and operation of macroalgae-based bioethanol supply chain network (MBBSCN) in Korea. A mixed-integer linear programing (MILP) problem was developed that considers the main characteristics of bioethanol supply chains, such as biomass degradation with time, biomass resources availability and geographical diversity, feedstock density and distribution of demand. The MILP model concurrently predicts the optimal network design, facility location, technology selection, capital investment, production operations and inventory control. The proposed optimization approach is illustrated through a case study biofuel supply chain in Korea. The result shows that 90 percentage of bioethanol demand based on E5 can be met by macroalgae produced in the country and the remaining 10 percentage should be imported from the outside of country or from another resource.

A possible future extension is to use another biomass resource to meet the fuel demand. The extra product can be using another section such as bioenergy section.. Furthermore, incorporating uncertainties into decision making of MBBSCN, such as fluctuation in demand, disruption in biomass supply, and is incentive.

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