A Spatially-Explicit, Multi-Period MILP Modelling Framework for the Optimal Design of a Hybrid Biofuel Supply Chain

Ozlem Akgul, a Nilay Shah, b Lazaros G. Papageorgiou a

a Centre for Process Systems Engineering, University College London (UCL), London WC1E 7JE, UK.
b Centre for Process Systems Engineering, Imperial College London, London SW7 2AZ, UK.

Abstract
This work presents a multi-period optimisation framework for a hybrid first/second generation bioethanol supply chain network considering uncertainty in biomass supply, biomass imports, biofuel sales and import prices. The model aims to maximise the expected net present value of the whole network and also controls the level of financial risk over all uncertainty scenarios. The model applicability is highlighted with a case study of hybrid bioethanol production in the UK in the time horizon from 2012 to 2020. The bioethanol demand for each time period is determined based on the UK domestic and EU biofuel targets. Biomass and bioethanol imports are also considered as a possible option to meet domestic ethanol demand. Sustainable use of first generation biomass crops has been taken into consideration to prevent any negative impact on food production.

Keywords: biofuel, supply chain optimisation, bioethanol, biomass.

1. Introduction
Liquid biofuels are considered as the promising candidates to address the following important problems the world is facing today: global climate change, depleting fossil fuel resources and increasing oil prices. These renewable fuels are classified as first, second and third generation based on the type of biomass and production technology used. First generation biofuels are produced mainly from food crops such as wheat and use established technology. On the other hand, second and third generation biofuels, also named as “advanced” biofuels, are produced from mainly non-food crops such as biomass waste and special energy crops. The production technologies for advanced biofuels are still under development. There is significant scope to integrate these emerging technologies with well-established first generation technologies in hybrid facilities to reduce any negative impacts on food production and provide better utilisation of biomass resources (Akgul et al., 2011).

One of the main challenges of the developing biofuels sector is the presence of uncertainties in supply and prices. These uncertainties must be taken into consideration during the assessment of those systems using any relevant advanced tools such as supply chain optimisation. A number of studies exist in the literature which uses such stochastic approaches (Kim et al., 2011; Mas et al., 2011; Tsang et al., 2007).

The objective of this work is to introduce a stochastic, multi-period mixed integer linear programming (MILP) model to maximise the expected net present value of a hybrid biofuel supply chain network. The problem statement is presented in section 2 while the
mathematical formulation is briefly described in section 3. A case study is discussed in section 4 and finally, some concluding remarks are drawn in section 5.

2. Problem Statement

The optimisation problem studied in this paper for the optimal design of a hybrid biofuel supply chain can be stated as:

Given are:

- locations of biofuel demand centres and their biofuel demand in each time period,
- biomass feedstock types and their geographical availability in each time period,
- unit biomass cultivation cost for each feedstock type,
- unit production cost of biofuel based on the feedstock type (hence technology) utilised,
- transport logistics characteristics (cost, modes, and availabilities),
- capital investment cost for the biofuel production facilities as a function of the production technology deployed,
- unit bioethanol sales and import prices,
- a target net present value for the network,

Determine the optimal:

- biomass cultivation rate for each biomass feedstock type and biofuel production rates in each time period,
- locations and scales of biofuel production facilities in each time period,
- flows of each biomass type and biofuel between cells in each time period,
- modes of transport of delivery for biomass and biofuel in each time period,
- level of financial risk,

So as to maximise the expected net present value of the supply chain.

3. Mathematical Formulation

The problem for the optimal design of a hybrid bioethanol supply chain under uncertainty is formulated as a multi-period, two-stage stochastic mixed integer linear programming (MILP) model. The first stage decisions include the optimal location and scales of plants. These are common across all scenarios. On the other hand, other variables are second-stage decisions which can be different from scenario to scenario (e.g. biofuel production rates). The objective is the maximisation of the expected net present value of the supply chain (ENPV) which is described as:

\[
ENPV = \sum_{s \in S} \sum_{s} \left( p_{b_s} NPV_s - TC_s \right)
\]

(1)

Where \( p_{b_s} \) is the probability of occurrence of scenario \( s \). \( NPV_s \), \( REV_s \) and \( TC_s \) are the net present value, total revenue and total cost in scenario \( s \), respectively. The objective function is maximised with respect to production, demand, sustainability and transportation constraints. Apart from the level of the expected profit, the level of financial risk in each scenario is also important. The financial risk can be defined as the probability of not meeting a target NPV, \( \Omega \) and is measured using a risk factor, \( RF \). The total financial risk is defined by:

\[
RF = \sum_{s \in S} p_{b_s} \Delta_s \quad s \in S
\]

(2)
where $\Delta_s$ is the positive deviation from the target NPV level. This deviation is defined through the following two equations:

$$\Delta_s \geq \Omega - NPV_s \quad s \in S$$

(3)

$$\Delta_s \geq 0 \quad s \in S$$

(4)

The degree of financial risk can be controlled using a tightening factor, $\lambda$ ($0 \leq \lambda \leq 1$):

$$RF \leq \lambda RF^*$$

(5)

where $RF^*$ is the maximum level of risk experienced without any risk constraints.

### 4. Computational Results

The proposed stochastic, multi-period model has been applied to a case study of bioethanol production in the UK in the time period from 2012 to 2020 using wheat (first generation feedstock) and wheat straw (second generation feedstock). The nine years from 2012 to 2020 has been divided into three time periods (2012-2014, 2015-2017, 2018-2020). The UK is discretised into 34 square regions (of each 108 km length) with 6 biofuel demand centers. The market bioethanol demand for each time period and demand centre is presented in Table 1. Uncertainty in biomass availability, biomass imports, bioethanol sales and import prices has been considered. The first three of these uncertain parameters is assumed to be uniformly distributed between -50% to +50% of their respective nominal values. Bioethanol import price has been assumed to change uniformly between 1.1 to 1.5 times the sales price to account for the import tariff. 50 scenarios have been generated using these four uncertain parameters. Without the presence of financial risk constraints, the expected net present value of the supply chain is determined as £0.96 billion for which the cumulative probability distribution function is given in Figure 1. A target NPV ($\Omega$) of £0.15 billion has been selected. Initially, 22% of the 50 scenarios are below the target. To see the effect of imposing financial risk constraints, a risk tightening factor ($\lambda$) of 0.25 has been applied. The resulting cumulative PDF can also be seen in Figure 1. The ENPV has decreased to £0.88 billion in this case whereas the percentage of scenarios below the target level has decreased from 22% to 12%. As can be concluded from the comparison of the two curves, the approach of the decision maker changes from risk-taker to risk-averse as the risk tightening effect is increased. The probability distributions for the two cases are shown in Figure 2. It is seen that the presence of financial risk constraints results in a narrower distribution of NPV (e.g. smaller standard deviation) which also implies a reduction in the level of financial risk.

Table 1. UK Bioethanol demand data per demand centre and time period.

<table>
<thead>
<tr>
<th>Demand centre</th>
<th>1st time period</th>
<th>2nd time period</th>
<th>3rd time period</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>261</td>
<td>374</td>
<td>487</td>
</tr>
<tr>
<td>13</td>
<td>834</td>
<td>1,194</td>
<td>1,554</td>
</tr>
<tr>
<td>19</td>
<td>851</td>
<td>1,219</td>
<td>1,586</td>
</tr>
<tr>
<td>23</td>
<td>750</td>
<td>1,073</td>
<td>1,397</td>
</tr>
<tr>
<td>27</td>
<td>342</td>
<td>490</td>
<td>638</td>
</tr>
<tr>
<td>29</td>
<td>897</td>
<td>1,284</td>
<td>1,671</td>
</tr>
<tr>
<td>TOTAL</td>
<td>3,935</td>
<td>5,634</td>
<td>7,333</td>
</tr>
</tbody>
</table>
Figure 1. Cumulative probability distribution function of the net present value for the fifty scenarios with and without financial risk constraints.

Figure 2. Probability distribution function of the net present value for the fifty scenarios with and without financial risk constraints.

Figure 3 shows the average fraction of ethanol and biomass imports in meeting the total ethanol demand over all time periods with and without financial risk constraints. As can be seen from the figure, both with and without financial risk constraints, imports occupy a significant fraction of the overall bioethanol demand in most of the scenarios.
A Spatially-Explicit, Multi-Period MILP Modelling Framework for the Optimal Design of a Hybrid Biofuel Supply Chain

5. Concluding Remarks

A stochastic, multi-period MILP modelling framework has been presented for the optimal design of a hybrid biofuel supply chain. The model has been applied to a case study of bioethanol production in the UK from wheat and wheat straw in the time horizon from 2012 to 2020. Uncertainty in biomass availability, biomass imports, bioethanol sales and import prices has been considered. The presence of financial risk constraints has also been investigated. The results indicate that incorporating financial risk constraints results in a reduction in the overall financial risk at the expense of reducing the expected net present value. In addition, biomass and bioethanol imports meet a significant portion of the total ethanol demand in most of the cases.

6. Acknowledgements

O.A. gratefully acknowledges financial support from the Centre for Process Systems Engineering (CPSE).

References


