ABSTRACT – The use of waste tallow as a feedstock can reduce costs and improve environmental performance of biodiesel production in comparison to vegetable oils. The objective of this work is to formulate an optimization problem to support decision making of feedstock blend for biodiesel production considering specificities of Brazilian regulations. Cold filter plugging point, cloud point, pour point, viscosity, cetane number, flash point and density were evaluated by prediction methods as a function of the blend composition, and the appropriate limits were imposed on each property. A numerical example of a multi-period problem is provided, with regulations that depend on the season and the country region where the fuel is to be used.

1. INTRODUCTION

Computational decision support tools are useful to cope with trade-offs in operation planning. Concerning biodiesel production, there are many drivers to the development of numerical optimization problems able to find optimal blends of feedstocks, such as: diversity of feedstocks with different fatty acids composition, legal regulations on biodiesel physical-chemical properties, dynamic prices, and the opportunity to reuse waste materials as inputs to biofuel production. Animal fats are an interesting material feedstock due to their low prices, but the presence of high amounts of saturated fatty acids (namely palmitic and stearic acid) may hinder its utilization. An appropriate blend with vegetable oils must be made to satisfy specification on properties such as viscosity and high cold filter plugging point (CFPP). The contribution of this work is two-fold: from the optimization point of view, standard approaches normally model the blending of biodiesel and petrodiesel (Bezergianni et al., 2011; Flood et al., 2016); regarding biodiesel property evaluation, most works focus on the experimental evaluation of multi-feedstock biodiesel blends (Yuan et al., 2017). This proposal looks for blends of vegetable oils and tallow with minimal cost, respecting constraints that depend on the season and market location.

2. METHODOLOGY

The fatty acids composition of vegetable oils and tallow was taken from Gunstone (2002). Assuming that the kinetics of the esterification of all triglycerides are the same and that all fatty acids are converted into FAMEs (fatty acid methyl esters), the FAMEs profile of the final biodiesel can be estimated. Then, the physical properties are estimated as follows: Cloud point (CP), Pour
point (PP), Cold filter plugging point (CFPP) and Flash point (FP) by the method developed by Su et al. (2011); viscosity and Cetane number (CN) by the method of Chang and Liu (2010), and density by the method of Pratas et al. (2011).

The objective function of the optimization problem is the minimization of the total cost of feedstock purchases, with purchase cost depending on period and feedstock, as in Equation 1:

\[
\min \text{Cost} = \sum_{t, \text{market, feed}} \text{FeedMass}(t, \text{market, feed}) \times \text{price}(t, \text{feed})
\]  

Property upper (ub) and lower (lb) bounds depend on time and region (market) (Equation 2):

\[
lb(t, \text{market, prop}) \leq \text{BiodieselProp}(t, \text{market, prop}) \leq ub(t, \text{market, prop})
\]  

The efficiency \( \eta \) of the reaction is a function of the considered feedstock (Equation 3):

\[
\text{BiodieselProduction}(t, \text{market}) = \sum_{\text{feed}} \eta(\text{feed}) \times \text{FeedMass}(t, \text{market, feed})
\]

3. PROBLEM DESCRIPTION

Three Brazilian regions, S (South), SE (Southeast) and NE (Northeast), were considered due to their economic importance. Table 1 summarizes arbitrary annual demand on biodiesel and legal specifications for CFPP according to the periods of the year. It must be noted that the NE region has an average temperature higher than the SE region, which in turn has higher average temperatures than the S region, explaining different CFPP bounds for each region.

Table 1: Demand on biodiesel and maximum limit to CFPP for each different region and period of the year

|        | S     | SE    | NE  |
|--------|-------|-------|-----|
| Demand (t) |       |       |     |
| Summer  | 1,000 | 2,000 | 800 |
| Fall    | 1,000 | 2,000 | 800 |
| Winter  | 1,000 | 2,000 | 800 |
| Spring  | 1,000 | 2,000 | 800 |
| CFPP (°C) |       |       |     |
| Summer  | 14    | 14    | 19  |
| Fall    | 5     | 8     | 19  |
| Winter  | 5     | 8     | 19  |
| Spring  | 10    | 12    | 19  |

The CFPP property has a lower limit that is constant and equal to -5°C, regardless of the period of year and region. The other physical properties are time and region independent and their limits are: -20 °C ≤ CP ≤ 40 °C; -20 °C ≤ PP ≤ 40 °C; 3 mm²/s ≤ Vi@40°C ≤ 6 mm²/s; 47 ≤ CN ≤ 70; 100 °C ≤ FP ≤ 200 °C and 0.85 kg/L ≤ Density@20 °C ≤ 0.9 kg/L. (ANP 45/2014 norm).

The problem statement is to find cost-effective blends of the available feedstocks that match the physical property constrains of the final biodiesel. For prices, two cases were considered: Case 1, with the average prices shown in Table 2, and Case 2, reducing tallow price to 2,000 R$/t at all periods. The indicated prices in Table 2 were taken from Brazilian data comprising the 2015-16 period.
Table 2: Brazilian market average prices for the vegetable oils and tallow according to period of the year (R$/t)

| Period | SBO  | PO  | BO  | SFO  | PKO  | TW  |
|--------|------|-----|-----|------|------|-----|
| Summer | 3,194| 2,850| 4,950| 8,130| 4,750| 2,550|
| Fall   | 3,340| 2,800| 4,575|10,080| 4,500| 2,900|
| Winter | 3,023| 2,825| 4,650|10,080| 4,775| 2,800|
| Spring | 3,008| 3,450|6,050 | 6,480| 5,650| 2,500|

SBO: soybean oil; PO: palm oil; BO: babacu oil; SFO: sunflower oil; PKO: palmkernel oil; TW: tallow.

4. RESULTS

The evolution of the optimal blend composition is shown in Table 3 for both scenarios:

Table 3: Mass Fraction of feedstocks in the blend

| Period | Region | Soybean oil | Palm oil | Tallow | Soybean oil | Tallow |
|--------|--------|-------------|----------|--------|-------------|--------|
|        |        |             |          |        |             |        |
| Summer | S      | 0.33        | -        | 0.67   | 0.33        | 0.67   |
|        | SE     | 0.33        | -        | 0.67   | 0.33        | 0.67   |
|        | NE     | 0.12        | -        | 0.88   | 0.12        | 0.88   |
| Fall   | S      | 0.39        | 0.61     | -      | 0.69        | 0.31   |
|        | SE     | 0.15        | 0.85     | -      | 0.57        | 0.43   |
|        | NE     | -           | 1.00     | -      | 0.12        | 0.88   |
| Winter | S      | 0.39        | 0.61     | -      | 0.69        | 0.31   |
|        | SE     | 0.15        | 0.85     | -      | 0.57        | 0.43   |
|        | NE     | -           | 0.25     | 0.75   | 0.12        | 0.88   |
| Spring | S      | 0.49        | -        | 0.51   | 0.49        | 0.51   |
|        | SE     | 0.41        | -        | 0.59   | 0.41        | 0.59   |
|        | NE     | 0.12        | -        | 0.88   | 0.12        | 0.88   |

In the real prices scenario (Case 1), only the 3 least expensive feedstocks were present in the optimal solution (soybean oil, palm oil and tallow). In the second and third periods (Fall and Winter), there is a decrease in the palm oil price, inducing its utilization. However, only for the NE region a biodiesel fully made of such oil meets the specifications, whereas for the S and SE regions it is necessary to include soybean oil to decrease CFPP. Regions with higher acceptable CFPP favour the use of low-cost, saturated-rich, animal fat, instead of soybean oil.

In Case 2, there is a larger incentive to consume tallow, changing the blend composition in periods 2 and 3. For the other periods, the blend between soybean oil and tallow of the first case remains optimum and therefore the solution is the same. The behaviour of increasing participation of soybean oil to decrease the cold properties of biodiesel is shown again when comparing the blends of a given period. Even when the constraint is less stringent (NE region, all periods), it is not possible to meet all specifications with a biodiesel made entirely with animal fat, demanding at least 12% of soybean oil. To compare the influence of feed compositions, Figure 1 provides a plot of all calculated properties in the biodiesel of the NE region of period 2 in both scenarios.

For Case 1, the solution is a biodiesel with 100% of palm oil, corresponding to a fuel with better cold properties (CFPP equal to 9.58 ºC, for instance). On the other hand, for Case 2 the amount of added soybean oil to the feedstock blend is the least possible (12%) to meet the constraints, particularly the CFPP constraint. The variation on other properties may be negligible (density) or
rather small (cetane number), but in all considered cases the CFPP constraint was active whenever tallow was present at the blend composition, demonstrating that it is the most important property to be taken into account when deciding the feedstock blend.

Figure 1: Comparison of biodiesel properties (NE region, Fall period).

4. CONCLUSIONS

A computational decision support tool based was presented to aid the optimal choice of feedstocks blend. To illustrate the approach, a multi-period scenario was evaluated for three regions in the Brazilian biodiesel market. The results show that the CFPP property is determinant in the optimal blend composition and regions with higher average temperature favour the use of waste tallow as raw material. A sensitivity analysis was performed on the tallow price, showing that it could replace palm oil if cheaper. Future work is to further develop the economic objective function, including other operational costs, such as feedstocks transportation and storage.

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