Economic Comparison of Continuous and Batch Production of Biodiesel Using Soybean Oil

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Continuing depletion of fossil fuel reserves and increasing environmental concerns have encouraged engineers and scientists to look for alternative, clean, and renewable fuels that can reduce fossil-fuels' negative environmental impact and secure the energy supplies. Biodiesel has been considered as one of the best candidates for these renewable fuels. For its production, transesterification reaction of triglycerides is recognized as a feasible pathway. This reaction can be carried out in continuous or batch reactors, however, most of the other unit operations, like decanters and distillation columns, are operated continuously. Most of the studies of biodiesel production have been done in continuous models. In this paper, we evaluate batch and continuous processing options for biodiesel production from the economical point of view. The economic feasibility of biodiesel as well the plants configuration not only depends on technical design aspects but also on other important factors such as seasonal variation of feedstock, transportation costs, and storage costs of material. Therefore, our comparison involves size of the market, transportation distance from supplier to producer facility, and feedstock availability of soybean oil by the allocation of supply of raw material. It was found that based on these aspects, batch processing shows interesting results and should be considered for production rather that continuous production as it is done today. Moreover, a sensitivity analysis provides more insights of the flexibility of batch processing when scheduling variation is considered. © 2012 American Institute of Chemical Engineers Environ Prog, 32: 11–24, 2013

Keywords: batch process; continuous process; biodiesel; stochastic simulation; economical analysis

INTRODUCTION (SECTION 1)

Over the past decades, the development of new technologies for renewable energy has become one of the most interesting topics around the world [1]. These technologies have resulted in promising alternatives for the replacement of conventional (fossil) fuels. A commonly mentioned example is biodiesel, which substitutes the petroleum-based diesel. This biofuel is a renewable, domestic resource with an environmentally friendly emission profile [2]. Biodiesel can be produced from the transesterification of vegetables oils and alcohol, where soybean oil is employed as the most common resource of fatty acids and methanol is widely considered the most cost-effective and readily available alcohol. Among other examples of raw materials are rapeseed, palm oil, sunflower, coconut, linseed, etc., which also contain the fatty acids necessary for this transesterification [3]. Several articles have addressed the production of biodiesel; some of them started by studying the transesterification reaction and obtaining the kinetic parameters [4,5], others have considered different pathways for the production of this renewable fuel [6–8] or different resources to obtain the fatty acids used in the reaction [2,9,10]. Also, other works have focused on the optimization of biodiesel production by changing different parameters, such as reaction temperature and time, alcohol ratio, viscosity, and catalyst [11–14].

Recently, investigations on commercial biodiesel production have focused on process technology and economical assessment. Available literature and existing computer tools mostly deal with optimal design of continuous processes. Given the seasonal variability of feed stock, batch processes can be a good alternative to continuous processing. However, very few people have given attention to batch processing of biodiesel. One of the most common advantages of batch processes over continuous processes is their high flexibility. These processes allow engineers to manipulate variations in feedstock and product specifications, making the process more adjustable to the requirements of a specific design.

One of the most important decisions that an engineer has to face when designing a chemical plant is the operation mode. This decision implies that the best process which

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Figure 1. Biodiesel supply chain overview. [Color figure can be viewed in the online issue, which is available at **wileyonlinelibrary.com**.]

minimizes the costs and maximizes the yield has to be found. Making this decision will affect the product quality and the viability of the process. Therefore, several aspects such as production rates, operational process, recycle options, hazardousness of chemicals, possibilities of energy integration, and economic analysis must be considered [15]. Many paths may be available to produce the same material, but the remaining question is which one would be the best and under which conditions. Comparison between batch and continuous operation has received little attention, only some cases are available but they referred to specific chemical process. For instance Wagialla, K. M *et al.* [16] present a comparison of some technical aspects regarding batch versus continuous refining of crude cottonseed oil. In this work, researchers evaluated the percentage of refining loss, refined oil color, caustic soda consumption based on the initial crude-oil free fatty acid content and showed that continuous refining of cottonseed oil is more efficient in each of these performance criteria, particularly the percentage of refining loss. In Goršek *et al.* [17], the objective was to highlight the important factors which govern the selection of a simplified operation mode (i.e. batch/continuous) using a single-purpose equipment. Such factors were production capacity, recycling, and energy integration with heat storage. As a result, it was shown that the most profitable operation mode, in terms of Net Present Worth (NPW), was the continuous model with recycle loops and energy integration. However, in a second part of the paper [18], the study was focused on the advantage of a batch model with multipurpose equipment. The same example was used to produce a specialty chemical, and the results showed that batch process with multipurpose equipment was more profitable than a batch process with single-purpose equipment and even more profitable than the continuous one. Finally, Fonseca *et al.* [19] compared the behavior of batch and continuous processes using the reaction rate constants found in the open literature for transesterification of vegetable oils. In their study, they presented that a series of CSTRs can be an industrially feasible choice for replacing batch transesterification reactors in large scale biodiesel plants; moreover, it was shown that the loss in productivity caused by changing from batch to continuous process can be compensated by means of using higher catalyst concentrations.

Literature concerning just the estimation of biodiesel production cost has been presented separately for continuous models [11,20,21] and batch models [22]. These works were based on capacity plant and different process technology, such as energy integration, variation in catalytic processes or availability of raw material. As an example, Sakai, T. *et al.* [22] show a manufacturing cost comparison between continuous processes with the production of biodiesel in a batch model. This comparison was based on the type of catalyst (homogeneous and heterogeneous alkali) and method of purification of biodiesel. As a result, they showed that their batch processes were relatively expensive compared with the continuous process shown by [23], but are competitive when they considered the glycerol credits and underestimation fixed cost.

As it can be seen, the literature of economic comparisons between batch and continuous process for the production of biodiesel (especially from soybean oil) is limited. On the other hand, previous literature, related to batch and continuous production, agreed that raw material is the largest contributor to the production cost; for instance, Haas, M. J., *et al.* [21] demonstrated that 88% of the total estimate production cost was due feedstock soybean oil cost, whereas in Myint L.L *et al.* [11], this raw material cost corresponded to 90% of the total annualized cost. This issue becomes more challenging when considering the market availability of soybean oil and distance to the biodiesel production facility. Therefore, in this paper we propose an economic comparison of continuous and batch process of biodiesel production having as the decision criteria the size of the market, its distance, and feedstock availability.

This paper is arranged in the following order: Section 2 introduces a brief background of biodiesel supply chain management, which includes information about soybean market, soybean transportation, and biodiesel production. Then, Section 3 mentions some characteristics about continuous and batch processes followed by Section 4 where the process description of these two models is explained. The economic analysis is shown in Section 5. Finally, Section 6 summarizes the conclusion of this work.

BACKGROUND (SECTION 2)

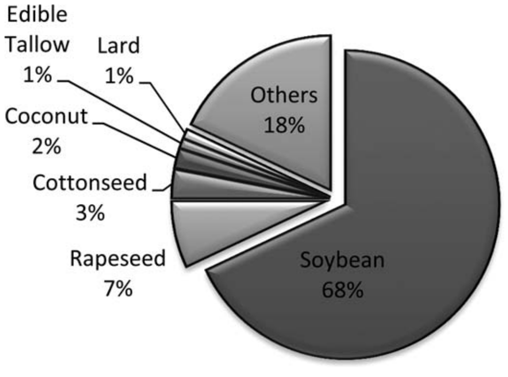
Biodiesel Supply Chain Management

The supply chain management assesses the challenges existing for bringing biofuel production up to scale [24–26]. These studies include the production and transportation of the feedstock from a farm to a refinery in the most cost efficient manner. The supply chain management for biodiesel is described graphically in Figure 1.

In the first part of the supply chain management, the feedstock production is considered. This section comprises issues such as land availability, seeding, growing, yield and environmental impact of growing the feedstock. Following to this section, we have the feedstock logistic. This stage has four smaller steps which are harvesting, storing, preprocessing and transportation of the feedstock from the cropland to refineries [25]. Then biofuel production is the third step. Here the feedstock (e.g. soybean) is converted through transesterification reaction in biofuel (e.g. biodiesel). The last two stages are related to the transportation and end use of the biofuel which focuses on how the consumers access the biofuel.

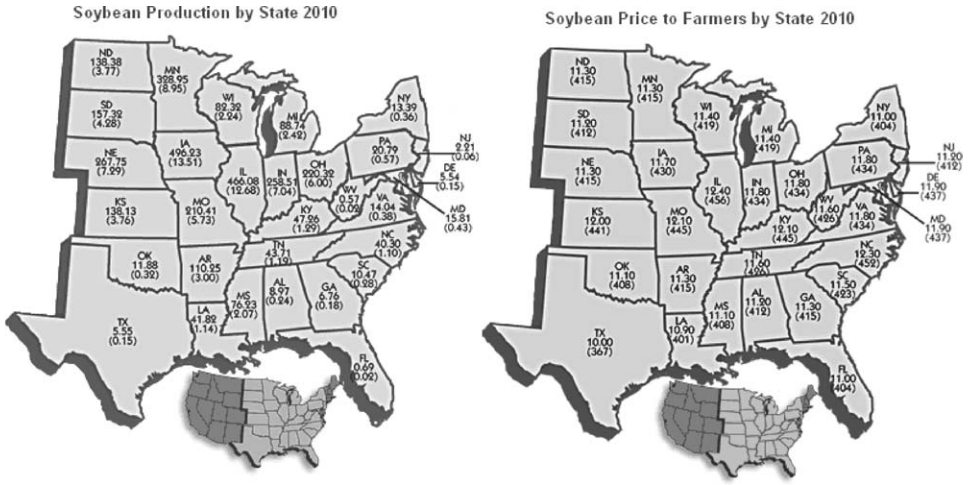
The supply chain management for biodiesel can affect significantly the economical assessment of biofuel production. For instance, the cost incurred in the feedstock logistic stage is one of the major costs drivers, and it has received minimal attention [24]. This could also be one of the causes that the cost of raw material contributes in 88% of the total estimate production cost. Ref. [26] considers three aspects regarding the economical evaluation of the feedstock logistic stage:

- Transportation vs. economy of scale: the cost of feedstock transportation and risk of supply instability can be affected due to the inherent scale economics that encourage the construction of large biomass refineries.
- Storage location: this aspect will depend on the feedstock, the planted, and harvest season. For example, most of the U.S. soybeans are planted in May and early June and harvested in late September and October [27]. The resulting biomass needs to be stored the rest of the year and this



Feedstock	Million Metric Tons
Soybean	*6.52*
Rapeseed	0.72
Cottonseed	0.29
Coconut	0.17
Edible Tallow	0.12
Lard	0.08
Others	1.76
Total	9.64

Figure 2. U.S. fats and oils consumption 2010 [28].



Source: [28], (Dark area not estimated)
Production by State million Bushels (Million Metric Tons)
Price to farmers by state $/ Bushel ($/Metric ton)

Figure 3. Soybean production and price by state 2010 [28].

can be done either in the fields where feedstock is harvested or in the refinery.

- Capital cost of inventories: the storing location of inventories is one of the key decisions in the design of a supply chain for biofuels. This aspect will evaluate convenient way to store the inventories.

Soybean Market

There are different types of oils and fats that may be used to produce biodiesel. Figure 2 includes various oils such as canola, cottonseed, coconut, edible tallow, lard, and others (corn, palm, palm kernel, peanut, sunflower, and safflower). As it is shown in this figure, soybean has been the most widely used in the U.S., contributing to 68% of the fats and oils consumption of 2010. Besides, in 2010 soybeans represented 58% of world oilseed production and 35% of those soybeans were produced in the U.S [28]. Finally, soybeans are about 90% of U.S. total oilseed production. Among other characteristics, soybean has expandable harvest areas, cheapest feedstock among other vegetables oils and high quality due to its low free fatty acids and high purity. Therefore, in this work soybean is chosen as the feedstock for the production of biodiesel.

Three types of soybean oil can be encountered for the production of biodiesel: crude oil, refined, and bleached. Although, high conversion can be achieved through conventional technology, it is only suitable when refined oils are employed [29]. Therefore, refined oil is used in this paper; besides, the kinetic model was obtained from refined and bleached soybean oil by Noureddini and Zhu [5]. Refined oil refers to the amount of free fatty acid (FFA) which should be lower than 0.5 percent in order to avoid saponification, and to make the downstream processes of biodiesel after the reaction section less complicated. The drawback of using refined oils is its price, around 1000 to 1234 U.S. $/ton, while for crude oil, waste oil, or cooking oil, the price ranges can be around 110 to 320 U.S. $/ton but the amount of FFA is considerable high [29].

Soybean production cost may vary for each region in the U.S. For instance, the Midwest soybean producers generally have higher yield and lower cost per acre than Southern and Easter producers [27]. Figure 3 (left side) shows the soybean production and price by state in 2010. It can be seen that Iowa and Illinois have the highest production with 13.51 and 12.68 million tons, respectively; while West Virginia and Florida have the lowest production both with 0.02 million tons. On the other hand, Figure 3 (right side) shows the price to farmers by state, as it can be seen Illinois and North Carolina have the highest price with 457 and 452 $/ton, respectively, while New York and Louisiana have the lowest price with 404 and 401 $/ton, respectively. This is important information that can provide the investors with criteria to find promising locations of biodiesel production plants.

Soybean Transportation

Transportation cost of feedstock plays an important role in the supply chain management, especially in the feedstock logistic since influences economically the location of a biodiesel facility. Generally, this cost is a function of the method of transportation used. The selection of transportation depends on the availability of infrastructure, quality and distance. For instance, trucks, rail, or barges may be used to move the feedstock along the supply chain, each with a different cost per ton per distance. U.S. has an efficient rail system, extensive highway and barge infrastructure that make the average cost of moving U.S. crops from farm to vessel the lowest of any major grain and oilseed exporting country [30]. Usually farmers move their production by truck over “farm to market” roads. Many farmers own trucks capable to carry up to 30 metric tons and their most common practice is to truck soybeans by a grain elevator where the soybeans are unloaded, combined with soybeans from other farms. The second transportation mode is rail. Most soybeans and grains are moved in upwards of 40,000 large hopper cars that carry 80 to 90 metric tons each. Finally, barges moves over inland waterways. The U.S. has a widespread system of waterways that stretch from the Upper Mississippi River and its tributaries in Minnesota all the way to the Gulf of Mexico. In this paper, the transportation cost was determined based on the study proposed by Ref. [31] where a comparison of transportation costs for various locations is shown. We used a linear regression model to represent this information in to linear equations that relates the transportation cost with distance depending on the method of shipping (truck or rail). In order to obtain the transportation cost in units of $/miles, the distance *d* must be expressed in terms of miles. As a result, in this paper the transportation cost is calculated based on the first equation shown in Table 1 (i.e. truck).

Table 1. Transportation cost for soybean regarding the distance *d*

Method	Unit ($/miles)
Truck	0.1354 d + 3.1011
Rail	0.044 d + 4.6438

Biodiesel Production

Fatty acid methyl esters (FAME), well-known as biodiesel, are product of the transesterification process. This process is achieved by the reaction of triglycerides, e.g. contained in soybean oil, with an excess of alcohol (methanol) in the presence of an acid or alkaline catalyst. The reaction scheme is shown in Figure 4 [11]. This scheme represents the overall transesterification reaction where one molecule of triglycerides combines with three molecules of methanol produces one molecule of glycerol and three of methyl ester, well-known as biodiesel.

From the operation point of view, several factors that can affect the process -in terms of yield- have been investigated. Some of the relevant factors are the alcohol ratio, catalyst concentration, reaction temperature, and reaction time. Leung and Guo [9] discussed that an excess of alcohol ensures a complete conversion of oils or fats to esters, resulting in a greater ester conversion in a shorter time. On the other hand, an excess reaction time will lead to a reduction in the product yield due to the backwards reaction of transesterification [32]; therefore, for maximum yield the reaction time must be less than 90 minutes [3]. Temperature also influences the reaction and yield of the biodiesel product. A higher reaction temperature can decrease the viscosities of oils and result in an increased reaction rate, and a shortened reaction time.

BATCH VS. CONTINUOUS (SECTION 3)

A batch process is one in which a finite quantity of product is made during a period of a few hours or days. In contrast, in a continuous process, the feed is sent continuously to a series of equipment, with each piece usually performing a single unit operation [15]. In the literature, it has been found that one of the most relevant difference between continuous and batch process is the size of operation; although, it is not the only aspect, noticeably influences in the selection of the mode. Other aspects have been found in comparison studies, such as seasonal demand, storage facilities, lifetime of the product, hazard operation, and operation labor. One advantage of batch process over continuous is its flexibility. For instances, in batch processes the same equipment can be used for multiple operations and depending on the seasonal demand, batch processes can operate for only part of the year. On the other hand, the continuous processes to be profitable, their plants need to be large and operate throughout the year, and the storage facilities can be considered to overcome the feedstock availability and seasonal demand but the production cost will increase. Turton *et al.* [15] presents a complete summary of considerable distinctions between these two types of models.

PROCESS DESCRIPTION (SECTION 4)

In general, the biodiesel production involves four important steps and one extra step for the treatment of the byproduct, glycerol. The first step involves the reaction, where the transesterification of triglycerides results in the formation of

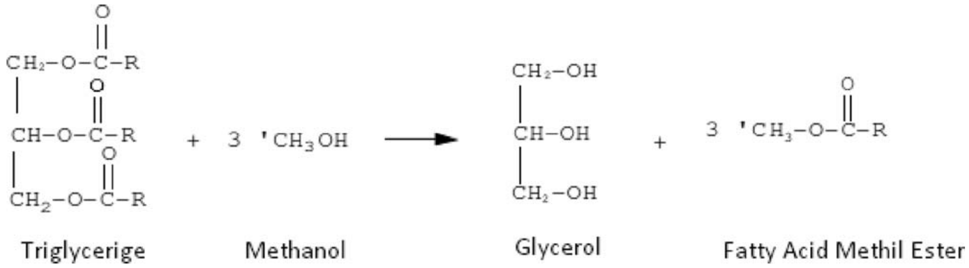


Figure 4. Transesterification reaction scheme.

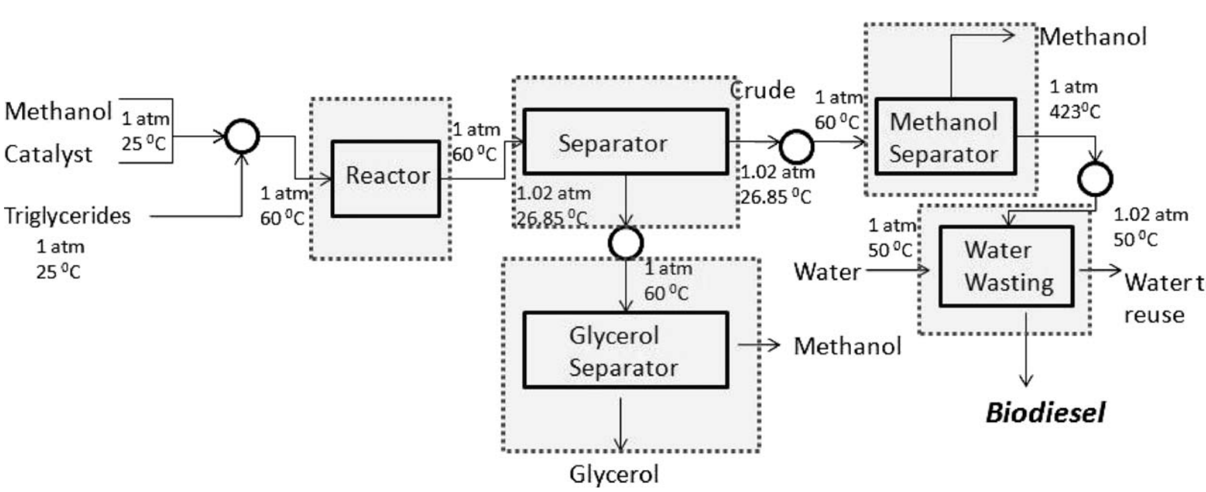


Figure 5. Schematic Process flow for biodiesel production.

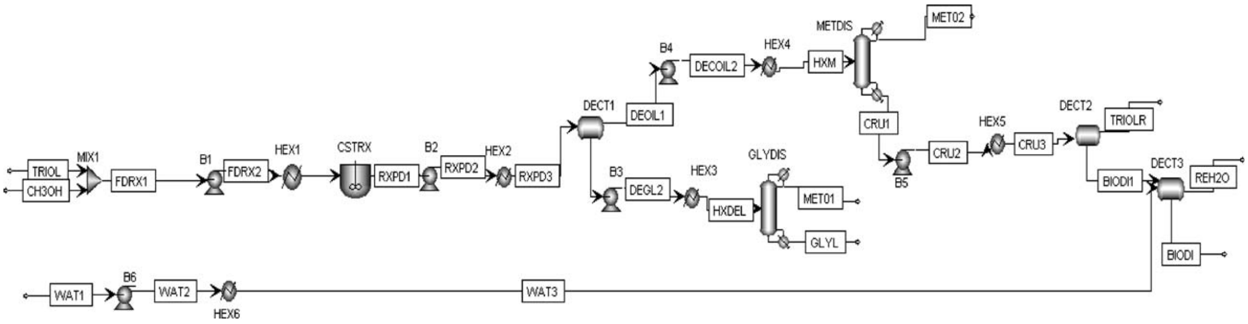


Figure 6. Continuous model for biodiesel production.

Table 2. Multibatch DS conditions

Process	Policy options	Task specification	Model options	Design conditions
Glycerol–methanol separation	Constant reflux ratio	Simulation	Semirigorous	Column: rectifier Reflux ratio: 1.05
Methanol–methyl ester separation	Constant reflux ratio	Simulation	Semirigorous	Column: rectifier Reflux ratio: 1.5

methyl ester (biodiesel) in presence of an alkaline catalyst (e.g. sodium hydroxide). After the reaction process, the following step (second step) is the separation of biodiesel from the rest of the products such as glycerol and the remaining catalyst. This step is performed in a decanter resulting in two streams, one directed to the glycerol separator (extra step) and the other stream directed to the methanol separator (third step). Finally biodiesel purification by washing with water is the final step (fourth step). For the purpose of this study, the biodiesel production flow sheet was based on one of the separation configurations presented in [11]. This configuration consisted on the separation of biodiesel and glycerol first, and then water washing after removal the methanol. This scheme is shown in Figure 5.

Continuous Model

The configuration for continuous production of biodiesel was simulated using ASPEN plus [33], and it is presented in Figure 6. First, the catalyst (NaOH) is mixed with methanol before it is charged into the reactor at 60°C and 1atm. A CSTR type was used. It is important to highlight that the thermal decomposition temperature for FAME and glycerol are 250°C and 150°C, respectively, so during the process the temperature was remained below these levels. After the reaction process, the outlet stream is sent to the heat exchanger at 1atm and 25°C, the stream is then sent to the first decanter (DECT1) for glycerol and biodiesel separation. The exit of glycerol stream has only 44 wt% concentration; therefore, this stream is sent to the heat exchanger (HEX3) before sending it to the glycerol distillation column (GLYDIS) in order to remove the glycerol. On the other hand, the biodiesel stream (DEOIL1) from decanter (DECT1) is sent first to the heat exchange (HEX4), then to the methanol distillation (METDIS) for removal of methanol. Then bottom biodiesel stream from (METDIS) is cooled down in a heat exchanger (HEX5) and then sent it to decanter (DEC2) where all the triglycerides (TRIOLR) remained from the reaction is removed. Finally, the biodiesel stream is sent to the third decanter (DECT3) where water washing take place. The resulting biodiesel stream has 99.67% purification which fulfills

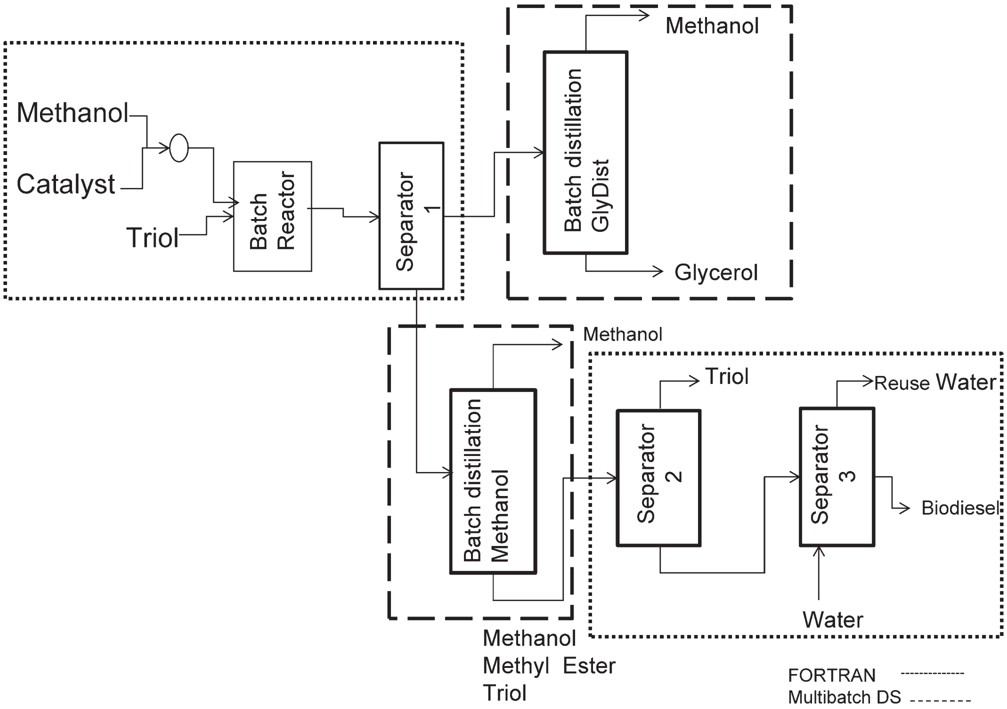


Figure 7. Batch model for biodiesel production.

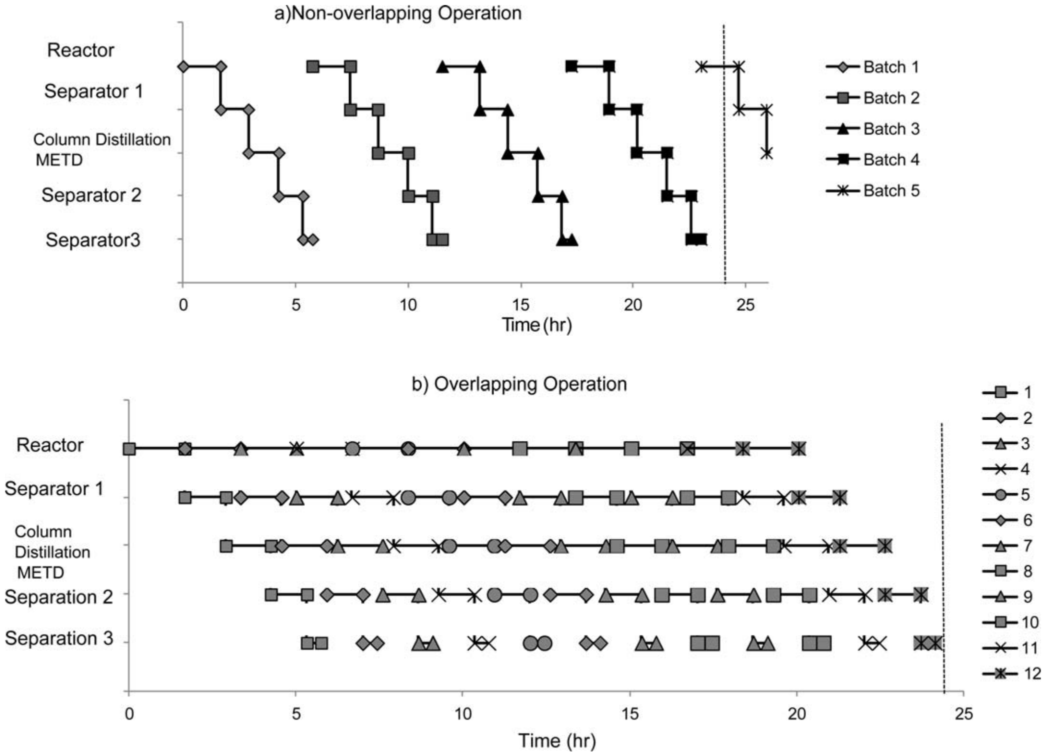


Figure 8. Gantt chart for biodiesel production.

the ASTM (American Society for Testing and Materials) standard requirements.

Batch Model

The batch model for production of biodiesel follows the same idea presented in the process description. However, this model uses batch reactor and batch distillation columns for separation of glycerol and methanol, and for purification of methyl ester. A general view of this model is presented in Figure 7. The reaction part was simulated using FORTRAN for the solution of differential equations resulted from the mass balance [34] while *Multibatch*DS software was

Table 3. Processing times

Stage	Batch time (h)
Reactor	1.67
Separator 1	1.23
Column distillation METD	1.35
Separator 2	1.1
Separator 3	0.42
Total time for 1 batch cycle	*5.75*

Figure 9. Distribution of the production plants.

employed to simulate batch distillation. *Multibatch*DS is a unique professional batch distillation system that offers multiple levels of models for batch column configurations, operating modes, fractions, and products [35]. *Multibatch*DS includes various configurations of batch distillation columns and examines the challenge involved in their dynamics. Some of the configurations presented in *Multibatch*DS are the rectifier (conventional column), middle vessel and stripping column. In this paper, the first configuration is employed to design the glycerol-methanol separation as well as the methanol-methyl ester separation column. Table 2 shows the design conditions used for the purpose of this paper.

Batch Scheduling

The production of batch processes requires to be scheduled due to short life cycles of the products and the multiproduct facilities in which the various products share the same equipment [36]. The manufacturing process of biodiesel follows a recipe specified by a set of processing tasks with fixed operating condition and fixed processing times. These tasks can be represented in a chart, usually known as Gantt chart, where the time activities are also involved at each stage of the process. Two kinds of operations can be found, non-overlapping in which each batch is processed until the proceeding one is complete or overlapping operation in which the idle times are removed in order to make batch production simultaneous. Figure 8 shows the Gantt chart for biodiesel production where the non-overlapping and overlapping operations are compared. Based on the processing time at each stage presented in Table 3, it can be seen in Figure 8 that with overlapping operation more batches per day can be performed which makes this operation more efficient. Therefore, the over lapping operation is chosen. For simplicity, it is assumed that the transfer times are negligible. The process time was developed on the basis of a biodiesel production capacity of 2404.33kg/batch cycle, were the cycle time for the overlapping operation is 1.67h. The reaction and the distillation time processing were given to the solution of mathematical models while the separator times were determined by heuristic knowledge [37].

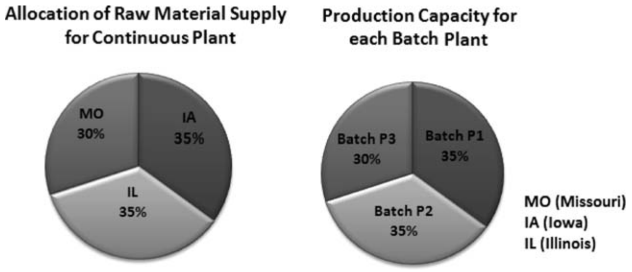


Figure 10. Raw material supply and production capacity.

ECONOMIC ASSESSMENT (SECTION 5)

Once again, the purpose of this paper is to compare continuous with batch processes for biodiesel production in terms of operation, capacity, transportation costs, and feedstock availability. Therefore, in this section we present an economic assessment which refers to the evaluation of fixed capital cost, and total manufacturing cost to produce biodiesel. Initially, the plant capacity is determined based on the designs of these two operation modes (showed in Section 4), for instance, the production capacity of the continuous plant is 20,868.40ton/yr while in one batch plant is 2404.33kg/batch. We decided to distribute the capacity of the continuous plant in three batch plants located in different states with different percentage of distribution. The continuous plant will be located in the middle of these batch plants and the soybean oil facilities. As a result, Iowa-OI- (Batch P1), Illinois-IL- (Batch P2), and Missouri-MO- (Batch P3) are the three states for the batch plants, and at the same time, the location where the feedstock will be provided for all plants. The selection of the batch plant locations was based on the availability of the soybean production in the U.S. As mentioned before, Illinois and Iowa are the two states with the highest production. Figure 9 shows the possible locations of the four biodiesel production plants in the Midwest. Point A represents the location of the continuous plant, while points B, C, and D are the locations Batch P1, Batch P2 and Batch P3, respectively. The darker points are some crushing facilities located in the area. (Information of soybean facilities can be found at Ref 31). On the other hand, Figure 10 summarizes the raw material distribution for the continuous plant as well as the production capacity of each batch plant. As it can be seen in the left side of this figure, 30% of the soybean oil will come from Missouri while 35% from Illinois and Iowa, respectively. Illinois and Iowa have the highest percentage since they have the highest production of soybean oil. In the right side, it can be observed that the same percentage is distributed for the production capacity of each batch plants.

The total cost of soybean in the continuous plant includes the transportation and its production costs. This information is shown in Table 4 where the distance (miles) from each soybean oil facility to the continuous plant and their corresponding cost are also presented. Comparing these values, it can be seen that the transportation cost just represents the 4.4% of the total cost of soybean oil. This small percentage is the result of the high production cost of the soybean

Table 4. Total cost of soybean

Origin	Price ($/lb)	Distance (miles)	Production cost (millions $/yr)	Transportation cost (millions $/yr)	Total cost (millions $/ton)	% Transportation cost
Iowa (IA)	0.50[a]	447	9.07	0.52	9.59	5.5
Illinois (IL)	0.56[b]	296	10.06	0.35	10.42	3.4
Missouri (MO)	0.50[a]	336	7.77	0.34	8.12	4.2
Total			*26.91*	*1.22*	*28.13*	*4.4*

[a] AGP corporate.
[b] ADM company.

Table 5. Operating cost

Item	Cost (U.S.$)
Raw materials [19,38]	
Soy bean oil (Triol)	(See Table 4)
Methanol	$0.320/kg
Hydrochloric acid HCl	$0.176/kg
Sodium hydroxide NaOH	$0.617/kg
Water	$0.067/1000kg
Utilities [16]	
Electricity	$0.06/kWh
Steam (10 barg, 184 C)	$14.19/GJ
Cooling tower water (80f to 100 F)	$0.354/GJ
Additional operating cost	
Plant operators base rate	$12.50/h
Wastewater treatment [11]	$2.64 e-3/kg

(95.6%). Therefore, the effect of feedstock transportation in biodiesel production is not significant in its cost.

Additional to the feedstock costs for biodiesel production, other costs such as waste treatment to protect environment, cost of personnel, administrative, utilities, and equipment costs can influence the manufacturing costs. These costs are included in the direct manufacturing cost (DMC), fixed manufacturing costs (FMC), and general expenses (GE). The DMC represents operating expenses that vary with production. Table 5 shows the chemical cost including raw material, catalyst, solvents, labor, and utilities costs for this economical assessment. The utilities involve the cost of electricity, steam and cooling tower water consumption. On the other hand, the FMC comprise property taxes, insurances and depreciation along with equipment costs and they are independent of changes of production rate. The third category (GE) includes managements, sales, finances, and research founding. The sum of these three categories results in the total cost of manufacturing (Eq. (1)).

$$\mathrm{COM}=\mathrm{DMC}+\mathrm{FMC}+\mathrm{GE} \qquad (1)$$

Where each category can be computed as (see Table 6):

$$\mathrm{DMC}=C_{\mathrm{RM}}+C_{\mathrm{WT}}+C_{\mathrm{UT}}+1.33C_{\mathrm{OL}}+0.03\mathrm{COM}+0.069\mathrm{FCI} \qquad (2)$$

$$\mathrm{FMC}=0.708C_{\mathrm{OL}}+0.068\mathrm{FCI}+\mathrm{depreciation} \qquad (3)$$

$$\mathrm{GE}=0.177C_{\mathrm{OL}}+0.009\mathrm{FCI}+0.16\mathrm{COM} \qquad (4)$$

Therefore, Eq. (1) can be rewritten as:

$$\mathrm{COM}=0.180\mathrm{FCI}+2.73C_{\mathrm{OL}}+1.23(C_{\mathrm{WT}}+C_{\mathrm{UT}}+C_{\mathrm{RM}}) \qquad (5)$$

where C_{OL} is the cost of operating labor, C_{WT} is the cost of waste treatment, C_{UT} is the cost of utilities, C_{RM} the cost of raw material, and FCI is the fixed capital investment. This latter value represents the cost of construction of a new plant, and involves the total direct plant cost (purchase equipment, piping, electrical systems, building) and total indirect plant cost (engineering and supervision, construction expenses, legal expenses). The complete information of the annual costs of raw material, operating labor, utilities along with estimations of the equipment costs and FCI are summarized in the Appendix (see Table A1). Among the assumptions used for the calculation of total manufacturing costs are: (1) the most economical available option was chosen, for instance, the material of storage tank and reactors were specified to be constructed of carbon steel. (2) The continuous process operating hours for biodiesel plant were assumed to be 350-days/yr. (3) The depreciation is assumed to be as 10% of the FCI. (4) For equipment prices the Chemical Engineering Plant Index was $I_{2010} = 552.5$ [39].

Table 6 shows details about data and equations used to estimate total manufacturing costs. This table also compares the two processes studied in this paper, continuous and batch. As it can be seen, the total DMC is 2.45% higher in the continuous process than batch processes due to higher costs of feedstock, waste treatment, and utilities. For instance, the total cost of feedstock in continuous process represents 73% of the total manufacturing cost while in batch processes is 71%. On the other hand, it was found that the waste water stream in the continuous process contains 85.97% more of methanol compared to the stream in batch process resulting in higher waste treatment cost. The energy consumption was found higher in continuous process since batch distillation is more effective in the separation process (i.e. requires lower value of distillate X reflux ratio). In contrast, the operation labor cost was 65.66% higher in the batch plants due to equipment cleaning, preparation time, and operation of each unit. Figure 11 summarizes this comparison.

Figure 12 shows percentage values of components of total manufacturing discussed in Table 6 (e.g. DMC, FMC and GE). It can be seen that the total DMC shows to dominate the total manufacturing costs, for example, in continuous process this value represents 81.80% of its total manufacturing cost while in batch processes is 80.69%. As mentioned before, this difference corresponds to higher costs of feedstock, waste treatment, and utilities in continues process. On the other hand, the FMC in batch process represents 2.93% of its total manufacturing cost whereas in continuous model is 2.05%. The reason why this category is higher in batch processes is because this group includes the depreciation, local taxes and insurances and the plant over head costs that depend mostly on cost of operation labor which is higher in these processes (Table 7). Finally, the GE do not vary significantly since this category includes the administrative, distribution and selling costs along with research and development that is calculated based on the COM of each process.

Table 6. Multiplication factors for estimating manufacturing cost (millions of dollars)*

Factor	Description	Continuous	Total batches	% Difference
Direct manufacturing costs (DMC)				
Raw material	CRM	29.932	28.661	4.44
Soybean oil	–	28.139	26.867	4.5
Waste treatment	Cwt	0.018	0.013	38.48
Utilities	CUT	0.387	0.139	184.24
Operating labor	COL	0.319	0.957	−65.66
Direct supervisory	0.18COL	0.057	0.172	−65.66
Maintenance and repairs	0.06FCI	0.207	0.172	20.19
Operation supplies	0.009FCI	0.031	0.026	20.19
Laboratory charges	0.15COL	0.048	0.144	−65.66
Patents and royalties	0.03COM	1.174	1.166	−0.97
Total direct manufacturing costs	CRM+CWT+CUT+1.33COL+ 0.03COM+0.069FCI	32.173	31.445	2.45
Fixed manufacturing Costs (FMC)				
Depreciation	0.1FCI	0.345	0.287	20.19
Local taxes and insurance	0.032FCI	0.110	0.092	20.19
Plant overhead costs	0.708COL +0.036FCI	0.350	0.781	−53.99
Total fixed manufacturing costs	0.708COL + 0.068FCI + depreciation	0.805	1.160	−29.31
General manufacturing expenses (GE)				
Administration costs	0.177COL+0.009FCI	0.087	0.195	−53.99
Distribution and selling costs	0.11COM	4.306	4.274	0.97
Research and development	0.05COM	1.957	1.943	0.97
Total General Manufacturing Costs	0.177COL + 0.009FCI + 0.16COM	6.351	6.412	−0.66
Fixed capital investment (FCI)		3.451	2.871	20.19
Start up cost		0.345	0.287	20.19

Source: Ref [15].

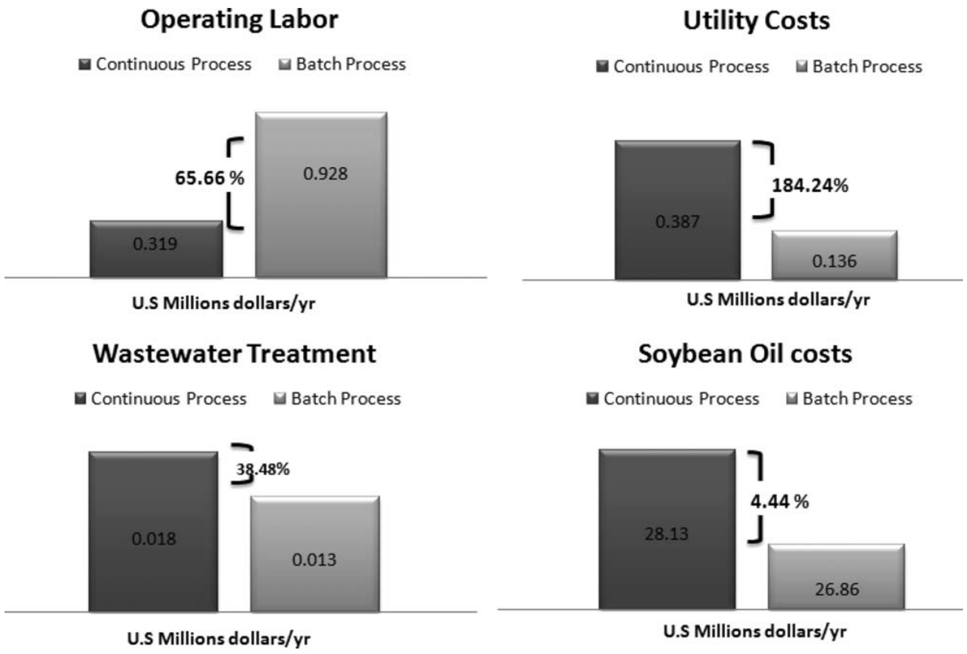


Figure 11. DMC comparison.

The total capital investment was calculated using equipment and fixed capital costs (Appendix Tables A2, A3). Figure 13 compares the total capital investment of continuous and batch processes. Although three batch plants were needed to have the equivalent production capacity to one continuous plant, it can be seen that the total capital investment is still higher in the continuous plant. The dominated factor to estimate this parameter was the purchased

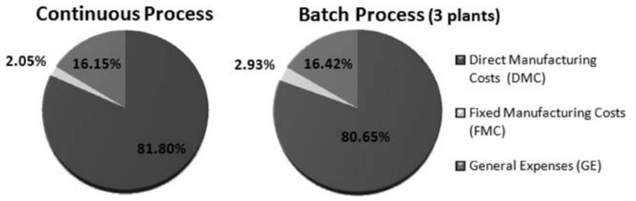


Figure 12. Comparison of the total manufacturing costs between continuous and batch processes.

Table 7. Cost of manufacturing (COM)

Total manufacturing cost (COM)	U.S. millions S/ton	U.S. millions $/yr
Continuous	1.88 e-3	39.15
Batch P1	1.78e3	14.04
Batch P2	1.96 e-3	13.68
Batch P3	1.80 e-3	11.03
Total batch	*1.84 e-3*	*38.77*

equipment costs where continuous process played an important role. For instance, the storage for oil in the continuous plant represents 28.8% of the total purchased equipment cost increases its fixed capital cost. This cost is consistent with results of storage facilities costs shown in [21]. In contracts, we did not considered storage facilities for soybean in the batch plants since we were assuming these plants were located in the same place where the feedstock facility was located.

As we mentioned before, the previous information was needed to compute the value of COM. Therefore, once we defined and calculated this information, the annualized total manufacturing cost of biodiesel was obtained. The results are summarized in Table 7. This table compares the COM values in two forms: millions S/ton and millions dollars/yr between continuous and batch processes. It can be observed that the manufacturing cost of the continuous plant is very close to the case when three batch plants are used. In other words, to produce around 21,000 ton of biodiesel per year, continuous process needs $0.3 millions of dollars more than having three batch plants. Although the difference represents a marginal increase (0.77%), it favors the batch process showing potential consideration for the industry of biodiesel.

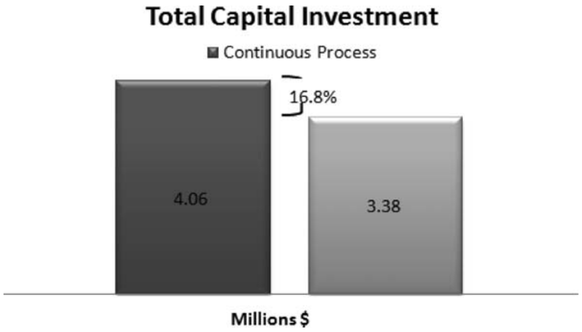


Figure 13. Comparison of the total capital investment.

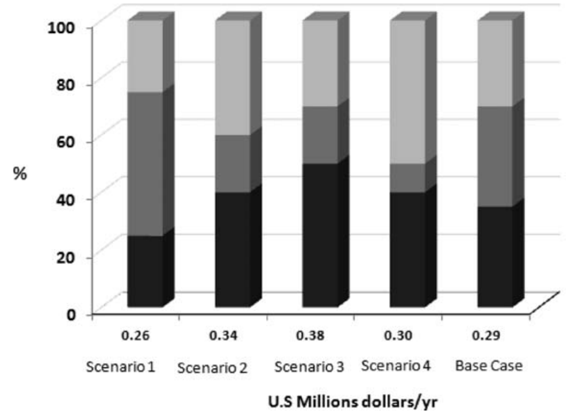


Figure 14. Comparison of the distribution capacity and raw material supply among different scenarios.

Table 8. Percentage of difference among different scenarios

Case	State	% Raw material supply/production capacity	% Of difference between Continuous and Batch				
			Millions $/yr	Soybean cost	Utilities	Waste treatment	Operating labor
1	IA	25	0.26	4.1	184.67	27.79	−65.58
	IL	50					
	MO	25					
2	IA	40	0.34	4.3	184.25	32.2	−65.66
	IL	20					
	MO	40					
3	IA	50	0.38	4.6	184.67	26.86	−65.58
	IL	20					
	MO	30					
4	IA	40	0.44	4.8	184	14.42	−65.58
	IL	10					
	MO	50					
Base Case	IA	35	0.37	4.5	184.24	38.48	−65.66
	IL	35					
	MO	30					

Positive values mean that there is an increase favoring batch process while negative values mean the opposite situation.

Table 9. Qualitative comparison between continuous and batch scenarios

	Best Process Batch Vs. Continuous				
Scenarios	**Soybean cost**	**Utility**	**Waste treatment**	**Operating labor**	**Overall cost**
1	Batch	Batch	Batch	Continuous	Batch
2	Batch	Batch	Batch	Continuous	Batch
3	Batch	Batch	Batch	Continuous	Batch
4	Batch	Batch	Batch	Continuous	Batch
Base case	Batch	Batch	Batch	Continuous	Batch

Finally, we carried out a sensitivity analysis in order to explore more possible scenarios where the percentage of production capacity and raw material supply were more highlighted. This analysis consisted of five scenarios where the fifth scenario is the base case (Figure 10). Thus, to perform this analysis, we changed the percentage of allocation of raw material supply for the continuous plant and production capacity of each batch plants. A summary of these results is shown in Table 8. Before analyzing the detailed information of this assessment, in Figure 14 we compared the five scenarios based on its difference on the COM value. For instance, Scenario 1 assumes that half of the biodiesel production is manufactured by Batch P2 and 50% of the supply of soybean oil comes from Illinois, meaning that Illinois dominates the production of biodiesel and supply of soybean. The remaining 50% is distributed equally between Iowa (Batch P1) and Missouri (Batch P3) for production of each batch plant and supply of raw material. It can be observe from Figure 14 that having half of the biodiesel production in Illinois and half of the feedstock supply coming from the same state, the continuous plant requires 0.26 millions of dollars more than three batch plants in order to produce around 21,000 ton of biodiesel per year (see Table 8). On the other hand, if Missouri dominates production and supply, meaning that half of feedstock supply comes from Missouri and half of production of biodiesel is manufactured in Batch P3 (scenario 4), the continuous plant would require 0.44 millions of dollars more to produce the same among of biodiesel per year. Although both scenarios favor the batch production, the latter one results more attractive. The reason why these scenarios favor batch production more in one case than in the other is due to the cost of feedstock and distance to the market (biodiesel plant). It is observed in scenario 1, that the cost of soybean oil is higher in Illinois (see Table 4) but the production facility is situated in same state where the supply comes from, which means that the feedstock would travel less distance, while in scenario 4, the feedstock facility is located 336 miles away from the production facility although the price of soybean oil is lower in Missouri. Same analyses were made for the remaining scenarios obtaining favorability for batch process in all of them. As a result, we observed that when the traveling distance from the facility to the market is high and the cost of feedstock is low, batch processes become more attractive to produce biodiesel. This is a positive feature of batch processing, especially when the feedstock supply is limited or variable due to, for example, seasonal production.

Moreover, Table 8 shows the percentage of difference between continuous and batch processes of other costs, such as soybean cost, utility costs, and so on. As expected, in terms of feedstock material, scenario 4 has the higher difference, meaning that the cost of soybean represents 4.8% more in continuous process than batch processes. It can also be seen that in all scenarios the difference in utility cost as well as operating labor cost does not have significant variation. In contrast, waste treatment varies from 14.42% to 38.48%. This outcome shows the high influence that the scheduling of batch processes have in the calculation of the waste treatment cost. We observed when the percentages of production capacity and supply of raw material were high; more batches per day were needed in a specific batch plant. For instance, in scenario 1, batch P2 had the highest production so 12 batches per day were needed, while batch P1 and P3 only six batches per day each (see Appendix Table A4), therefore, delegating more production in the batch plant will result in more water consumption, meaning more water to be treated. However, this observation comes along with the distribution of those percentages. Analyzing the base case scenario, the percentage of difference of waste treatment is the highest since the distribution of capacity and supply is relatively equal. Therefore, having better distribution in those percentages along the different batch plants will favor the batch production. This conclusion adds another positive feedback to batch processing giving the engineer more flexibility to set up the scheduling so the waste treatment can be minimized.

To summarize the results of this paper, we present Table 9 which describes a qualitative comparison between the proposed scenarios for continuous and batch processes. Based on these scenarios and the percentage of difference that compares them with the continuous plant shown in Table 8, we determined which process is the best to production biodiesel in term of costs. Once again, five costs were compared: soybean, utilities, waste treatment, operating labor, and the overall cost which is the same as the COM. As it can be seen in most of the cases, batch process is performing better than continuous process except for labor cost but overall batch process is better for biodiesel production.

CONCLUSION (SECTION 6)

In this paper, we compared continuous and batch processing of biodiesel production from soybean oil. The aspects for this comparison were based on the supply chain management for biofuels along with technical information concerning process utilities, waste treatment and operating labor. Modeling and simulation of continuous process were performed using ASPEN plus while batch processes, numerical methods and *MultiBatch*DS software for solution of batch reactor and batch distillation models were employed. From the results obtained in this paper, we found that batch processes favor biodiesel production over continuous processes when the size of the market, distance, cost of feedstock, and its availability are taken into account. Our first results show that the effects of feedstock transportation—which is taken into account only in the continuous plant—represented 4.5% of total cost of soybean oil. Although this effect is not significant in the calculation of raw material costs, it is considerable in the total manufacturing cost, since soybean cost represents 73% in a continuous plant while in batch plants is 71%. On the other hand, the flexibility of batch processes allows us to have three batch plants located in the feedstock facilities and they were scheduled depending on the feedstock supply and production capacity. Consequently, this scheme allows avoiding storage costs for soybean and obtaining interesting results that favor batch processes. For instances, we found that the waste treatment and utility costs were lower in batch processes due to fewer impurities in the waste water stream and less energy requirements due to lower distillate rate in batch distillation. Therefore, based on the different scenarios studied in this paper, production of 21,000 ton of biodiesel per year with a continuous process involves higher costs than doing it with three batch plants. Batch processing is therefore an attractive option to produce biodiesel and should be considered.

APPENDIX

As mentioned in this paper, there are many elements that influence the cost of manufacturing of specific products. The technical decisions regarding the operation and selection of raw material, among others, can play an important role in the estimation of the total manufacturing cost. The following tables present a list of important costs involved in the economic assessment to produce biodiesel. As mentioned before, the total manufacturing cost is divided into three categories, direct, fixed and general expenses. The direct costs involve the cost of raw material, waste treatment, utilities, and operating labor. These values are shown in Table A1 for

Table A1. Annual costs for the annual production of biodiesel from soy bean

Description	Annual cost (US Millions $/year) Continuous Model	Batch Model
Direct manufacturing cost		
Raw materials		
Soy bean oil (Triol)	26.867	26.867
Methanol	1.637	1.637
Hydrochloric acid HCl	0.010	0.010
Sodium hydroxide NaOH	0.145	0.145
Water	4.51 e-4	4.51 e-4
Subtotal raw material	*28.661*	*28.661*
Utilities		
Electricity	1.49 e-3	5.13 e-4
Steam (10 barg, 184°C)	0.374	0.133
Cooling tower water (80 F to 100 F)	1.08 e-2	5.02 e-3
Subtotal utilities	*0.387*	*0.139*
Others		
Wastewater treatment	0.018	0.013
Operation Labor	0.319	0.957
Direct supervisory and clerical labor	0.057	0.172

Table A3. Estimation of fixed capital investment (FCI) (millions $)

Fixed capital investment	Basis (% of purchased equipment)	Costs Continuous	Batch (one plant)
Direct costs			
Purchased Equipment	100%	0.685	0.190
Purchased Equipment Installation	47%	0.322	0.089
Instrumentation and Control	36%	0.247	0.068
Piping	68%	0.466	0.129
Electrical system	11%	0.075	0.021
Buildings	18%	0.123	0.034
Yard improvements	10%	0.068	0.019
Services facilities	70%	0.479	0.133
Total direct plant cost	*360%*	*2.465*	*0.684*
Indirect costs			
Engineering and supervision	33%	0.226	0.063
Construction expenses	41%	0.281	0.078
Legal expenses	4%	0.027	0.008
Contractor's fee	22%	0.151	0.042
Contingency	44%	0.301	0.084
Total indirect plant cost	*144%*	*0.986*	*0.273*
Fixed capital investment (FCI)	504%	3.451	0.957
Working capital (15% of total capital investment)	89%	0.609	0.169
Total capital investment		*4.061*	*1.126*

Table A2. Equipment costs (millions $)

Type	Description	Process Continuous	Batch (one plant)
Reactor	Transesterification	0.074	0.049
Storage tank (oil)	Storage of feedstock	0.198	-
Decanters			
Decanter 1	Separation glycerol/Oil	0.061	0.032
Decanter 2	Separation triol/biodiesel	0.043	0.029
Decanter 3	Biodiesel wash tank	0.026	0.017
Heat Exchangers	Reactor preheater	0.011	0.004
	GLYDIST1 tower preheater	0.003	1.61 e-4
	METDIST tower preheater	0.005	0.002
	Water washing preheater	0.002	0.001
	Total HEX	*0.02*	*0.006*
Coolers	Decanter 1 cooler	0.026	0.009
	Decanter 2 cooler	0.037	0.005
	Total Coolers	*0.064*	*0.014*
Columns	Glycerol/methanol separator (GLYDIST)	0.110	0.013
	Methanol/biodiesel separator (METDIST)	0.015	0.010
	Total Columns	*0.125*	*0.023*
Pumps, vessels, piping		0.073	0.020
Purchased Equipment		*0.685*	*0.190*

Table A4. Batch scheduling in different scenarios

Case	State	Production capacity	Batch/days
1	IA	25	6
	IL	50	12
	MO	25	6
2	IA	40	10
	IL	20	5
	MO	40	9
3	IA	50	12
	IL	20	5
	MO	30	7
4	IA	40	10
	IL	10	2
	MO	50	12
Base Case	IA	35	9
	IL	35	8
	MO	30	7

the annual production of biodiesel. This table is comparing each cost of one continuous plant with three batch plants. Most of these values depend on the production capacity of each plant mentioned in Section 5. The cost of utilities involves the electricity, steam and cooling tower water consumption. The cooling water can be supplied from a central facility such as a cooling tower while the steam can be produced by the evaporation at 10barg and 184°C. On the other hand, operation labor requirements depend on the number of process units and whether the process is continuous or batch these values change. Timmerhaus *et al.* [40] gives a typical labor requirements based on the units used in the process.

Table A2 illustrates the Equipment used in both continuous and batch plant and their respective costs. The design and costs calculation of reactors, decanters, heat exchangers, and coolers were based on the work by Hoffman, Z. [41] while distillation columns calculation was presented in Timmerhaus *et al.* [40]. It was assumed that 12% of the total equipment cost went to pumps, vessels and piping. Once the equipment cost was computed, the FCI (fixed capital investment) was calculated. The results are shown for the case of continuous and one batch plant in Table A3.

Table A4 presents the batch scheduling for each plant different scenario studied in the sensitivity analysis, this is the result of variation in the percentages of production capacity and supply of raw material.

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