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Techno-Economic Modeling of Soybean Oil Extraction with Hexane from 1980 to 2014

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Abstract.

Soybean is one of the main oil crop resources in the United States. It can be used as edible oil or biodiesel production. Additionally, the co-products (soybean meal, soybean hulls and gums) are able to be utilized in animal feeds and food additives. Hexane extraction is the most common approach in oil industry and has higher efficiency, above 90%, more than conventional mechanical expelling process. The advantages of hexane extraction are to increase the yield of oil products and short processing time. However, chemicals remaining, recycling and disposal are still a main concern in the industry. In this work, techno-economic analysis (TEA) was applied to evaluate the cost and profits of soybean oil extraction with hexane every 10 years from 1980 to 2014. For increasing the profits of this process, the analysis considered main product, soybean oil, and all co-products as well. The analysis based on soybean oil production of 40 million kg per year. The total profit is highly dependent on the material cost, which has the majority about 60%. Hence, with the increase in prices of materials, the revenues of the hexane process has also been increased. That leads to earning profits from the process.

Keywords. soybean oil, economic analysis, extraction, oilseeds, production

Introduction

Soybean, the main oil seeds in the world, takes 56% of world oil seeds production, and the US is the major producer with 32% (SoyStats, 2014). Soybean oil is the major resource of American vegetable oil consumption, and it takes around 54% of all vegetable oil resources (SoyStats, 2014). Generally, vegetable oil is obtained from mechanical process such as expelling or extrusion or solvent extraction. The solvent extraction is the efficient and usual method for oil production, and that can be applied to seeds with oil content lower than 20% and the oil crops with higher oil content (Bernardini, 1983). Hexane extraction is the traditional technique that is utilized in the industry because of its low cost and high solubility (Hammond et al., 2005, Sawada et al., 2014).

Recently, soybean productions, oil and meal, has significantly increased due to its nutrition values and wide applications not only in food industry but in other industries, non-food applications (Do et al., 2014). For conventional food and animal feeds usage, soybean is the good resource of oil, protein and fiber (Bader et al., 2011), and it is a good source of mineral and vitamins (Corley et al., 1999). With the population is getting increased, the need also increases. In the US, the area for soybean plantation has increased about 30% from 1980's to 2013 (SoyStats, 2014). For soybean meal, the side product, that also has been regarded as the potential material for animal feeds usage due to its high protein and fiber content. The meal annual production in the US reached 40 million short ton in 2013, and that has been increased around 47% from 1980s (SoyStats, 2014). In other application, soybean can be the suppliers of industrial raw materials and that can be used in the production of plastics, detergents, lubricants etc. (Perez and Nolasco, 2010, Perez et al., 2011).For obtaining high oil yield and good oil quality, the well process design is necessary. The physical properties of grain and the diffusivity are two major factors in solvent extraction process (Perez et al., 2011). During process, that includes dehulling, grinding, oil extraction, solvent recovery, oil degumming. However, hexane still has some defects such as its non-renewable fossil origin, leading to environmental pollutions and public health (Rosenthal et al., 1996, Oliveira et al., 2013, Tabtabaei and Diosady, 2013). Many researches have been using different solvents (Sawada et al., 2014, Bhagya and Srinivas, 1992, Do et al., 2014, Ribeiro et al., 2006) and different techniques (Myint et al., 1996, Domínguez et al., 1995, Eikani et al., 2012) to improve the oil yield and reduce the solvent consumption and environmental impact.

The first mathematic model was established by Karnofsky in 1949 to predict the oil extraction based on experimental data, and that mainly focused on soybean, cottonseed and peanuts. For vegetable oils production, the economic feasibility is another critical factor. There are few researches about oil extraction process. However, the oil extraction is the first step of oil applications. From some studies on economics of further oil utilizations, they included the oil extraction from oil seeds. Some research focused on different raw materials, processes and production scales. Nelson et al., (1994) conducted economic analysis of 100,000 ton/year biodiesel with beef tallow and methanol by acid catalysis. A similar study was performed by Noordam and Withers (1996) using canola seeds. Additionally, there were still other different economics modeling analyses for biodiesel production with different software (Bender, 1999, Zhang *et al*., 2003, Marchetti *et al*., 2008, Mlay *et al*., 2014).

According to prior studies based on oil conversion, those models can be regarded as a proper reference for economic analysis of hexane extraction process. The target of pilot and commercial scale production is trying to lower the capital investment and operating cost and to increase the yield and quality to earn more profits. However, each process unit could affect not only cost, but also have influence on yield and final profits. As the aspect to whole oil extraction process, the co-product is another critical factor which could increase total profits. High protein and fiber contents soybean meal and soybean hulls that are also valuable merchandise for other industries and markets.

This study will focus on traditional hexane extraction process. The products of hexane extraction include soybean oil, soybean meal and soy hulls. The goal of this study is to set up the economics model of oil extraction in industrial scale to predict the economic feasibility. That is not only used in oil industry, but expanded to the further biorefinery application and other relative industries.

Materials and Methods

Computer Model

SuperPro Designer v9.0 (Intelligen, Inc., Scotch Plains, NJ) was applied to conduct the Hexane extraction process of soybean oil production. That allows the processing characteristic, equipment and economic parameters to be defined along with conditions, capacity and characteristic for each stream (Wood et al., 2014).
According to the soybean process TEA model established by USDA (Haas et al., 2006), the hexane extraction process contained four main processes (Figure 1), they were soybean (crops) handling, oil extraction, oil degumming with hot water process (Ribeiro et al., 2006) and coproducts (soybean meal and soybean hulls) handling. The total capacity of soybean handling was 200,000,000 kg/year, and the final oil productivity was 34,000,000 kg/year with the total oil extraction rate of 94%.

Simulation

This study was conducting the analysis of hexane extraction from 1980 to 2014. That not only focused on the main product (soybean oil), but also included co-products (soybean meal and soybean hulls) (Table 1).

1. Independent factors
   Purchasing prices of soybean, market prices of soybean oil, meal (USDA ERS, 2014), hulls (Feedstuffs, 1980-2014) and utilities prices (EIA, 2014) were averaged every 10 years from 1980 to 2014. Additionally, steam was used as the heating resources in drying process, and the price was set as $12/MT.

2. Model assumptions
   The time of service of the model is 15 averaged, and loan interest was set at 7.0% per year. The equipment prices from 1980 to 2014 (Table 2) were estimated based on the CPI inflation index factor (Bureau of Labor Statistics, 2014), the price of 2014 was taken as the base. And the construction period and start-up time are 30 and 4 months respectively.

For each simulation result, the fixed capital costs, annual operating costs (AOC), annual revenues and total profits were considered. The gross margin percentage could be calculated according to Eq. 1.

$$Gross\ Margin\ (\%) = \frac{Revenues - Cost\ of\ good\ sold}{Revenue} \times 100\% \qquad Eq. 1$$

Table 1 Price input of materials and utilities for simulation.

	Soybean ($/kg)	Soybean meal ($/kg)	Soybean oil ($/kg)	Soybean Hulls ($/kg)	Electricity ($/kwh)
1980-1989	0.228	0.220	0.489	0.060	0.047
1990-1999	0.217	0.210	0.494	0.060	0.047
2000-2009	0.255	0.255	0.618	0.120	0.057
2010-2014	0.476	0.481	1.023	0.208	0.068

Table 2 Facility prices used in simulation ($)

		1980-1989	1990-1999	2000-2009	2010-2013
Material handling	Screw conveyor	44000	58000	80000	95000
	Silo	1654000	2194000	3022000	3596000
	Drum dryer I.	73000	96000	133000	158000
	Grinder	78000	104000	143000	170000
	Drum dryer II.	39000	51000	70000	84000
	Belt conveyor	123000	164000	226000	269000
Oil extraction	Hexane tank	111000	147000	202000	241000
	Hexane recycle	74000	99000	136000	162000
Meal handling	Drum dryer	61000	80000	111000	132000
	Screw conveyor	29000	38000	53000	63000
	Grinder	53000	70000	97000	115000
Oil degumming	Blending tank	112000	149000	205000	244000
	Drum dryer	24000	32000	44000	52000
Total Facilities		2475000	3282000	4522000	5381000

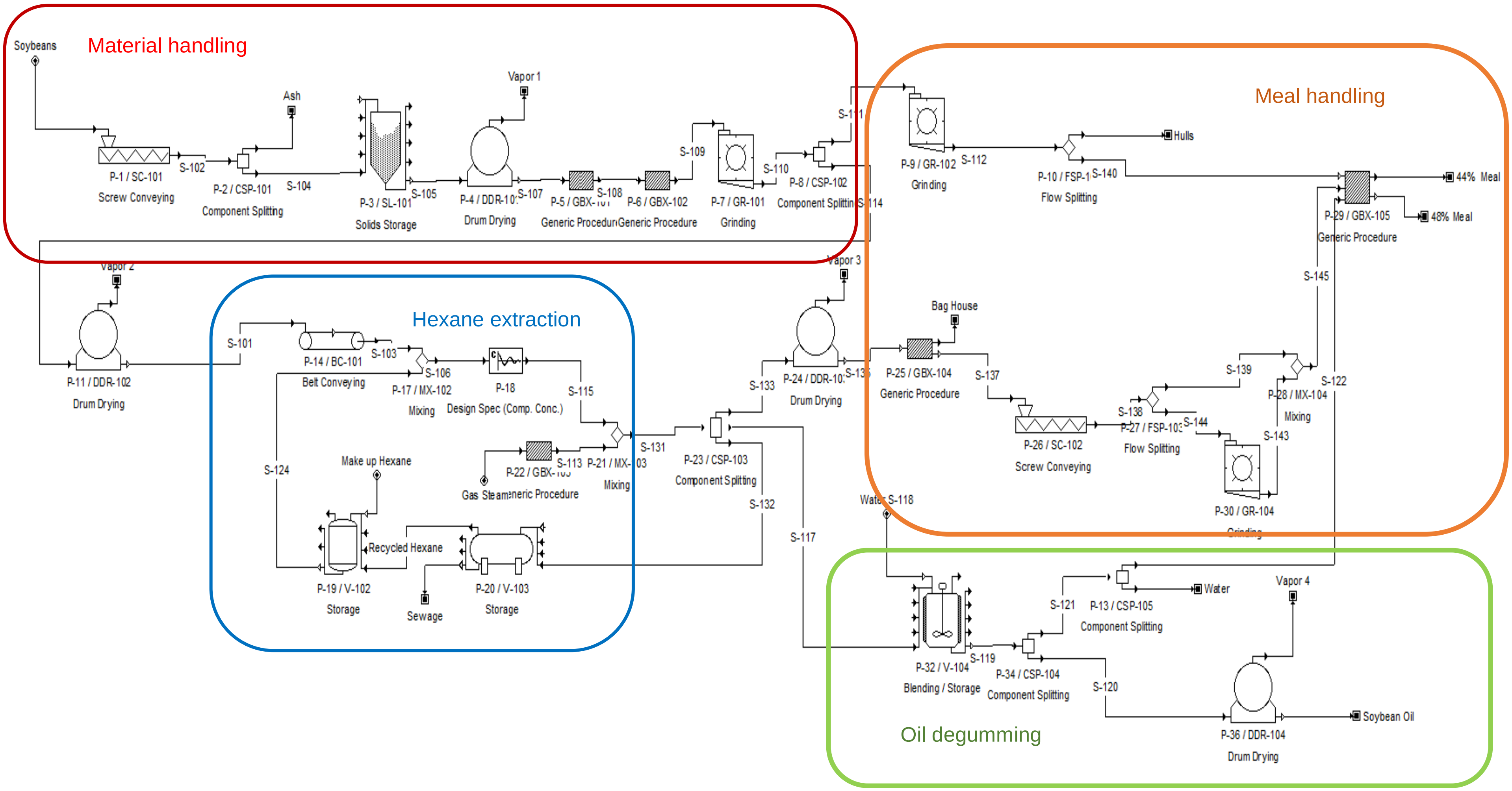

Figure1 The soybean oil hexane extraction model

Results and Discussions

Capital Costs

For building up a production stream in industry scale, the capita cost is the first investment that should be considered (Wood et al., 2014). That includes direct fixed capital (DFC), working capital and startup cost (Figure 2). For DFC, that is the majority of whole capital cost taking about 75%-85%. DFC comprises of total plant direct cost (TPDC), total plant indirect cost and contractor's fee and contingency (CFC). TPDC mainly indicates the hard ware of the production stream including equipments, installation, building, instrumentation, process piping and electrical work fees etc.; TPIC contains engineering and construction fees. However, the equipment purchasing fee takes about 30%-40% of whole TPDC (Table 3).

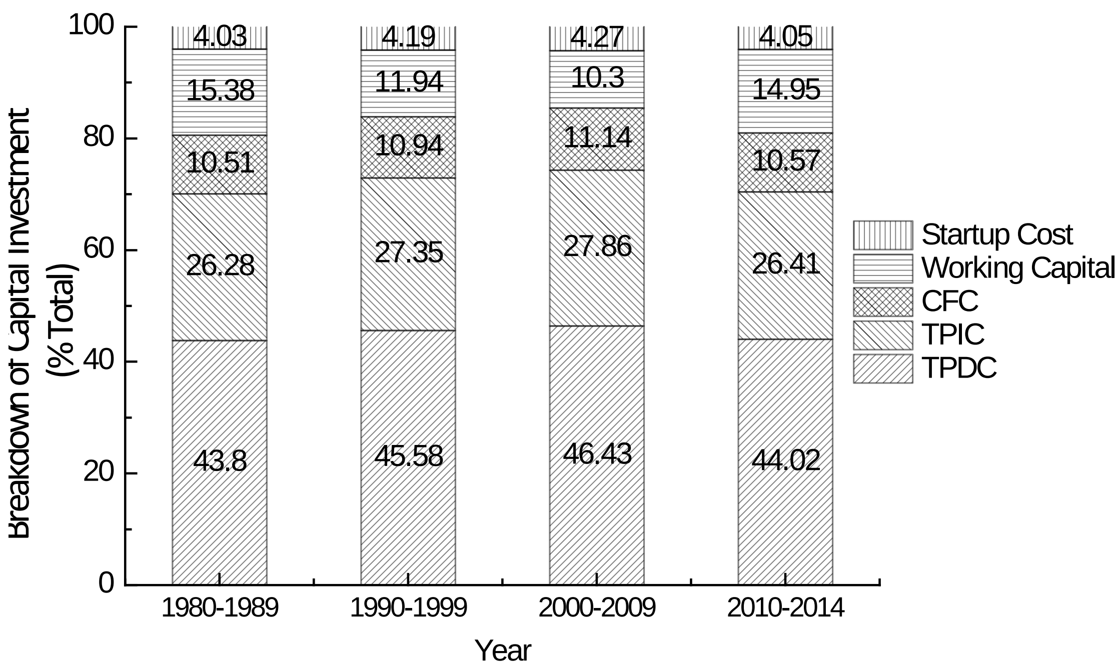

Figure 2 Break down of total capital investment.

In addition to DFC, working capital and start-up cost are also included in total capital investment. Based on the increase of CPI inflation index factor, DFC has been increased from 1980 to 2014. And, working capital and startup cost also increase corresponding to the change of DFC. Otherwise, the scale is also another critical factor that affects the total capital investment. As the scale of plant gets increased, the TPDC also increases because the hard ware is the fundamental of production stream. That eventually leads to the increase of total capital investment. In this model simulation, the total capital investment takes about 35% of whole costs as the operating cost is also included.

Table 3 Average total capital investment during different periods between 1980 to 2014 ($)

		1980-1989	1990-1999	2000-2009	2010-2014
TPDC	Equipment Purchase	3766000	4983000	6871000	8164000
	Installation	862000	1137000	1569000	1861000
	Processing Piping	1318000	1744000	2405000	2857000
	Instrumentation	1507000	1993000	2748000	3266000
	Insulation	113000	149000	206000	245000
	Electrical	377000	498000	687000	816000
	Building	1695000	2242000	3092000	3674000
	Yard Improvement	565000	747000	1031000	1225000
	Auxiliary Facilities	1507000	1993000	2748000	3266000
	Total TPDC	11709000	15488000	21356000	25374000
TPIC	Engineering	2927000	3872000	5339000	6343000
	Construction	4098000	5421000	7474000	8881000
CFC	Contractor's Fee	937000	1239000	1708000	2030000
	Contingency	1873000	2478000	3417000	4060000
DFC	TPDC+TPIC+CFC	21544000	28479000	39294000	46688000
	Working Capital	4110000	4057000	4737000	8617000
	Startup Cost	1077000	1425000	1965000	2334000
Total	DFC+Working Capital +Startup cost	26731000	33979000	45996000	57639000

Annual Operating Costs

For soybean oil production with hexane extraction, the operating cost includes facilities, utilities and material costs (Figure 3). Among these three sections, the material cost has over 85% of all operating costs, and that also influence the revenues of whole production stream directly. Besides, the utility and facility take 2%-4% and 8%-12% of operating costs individually.

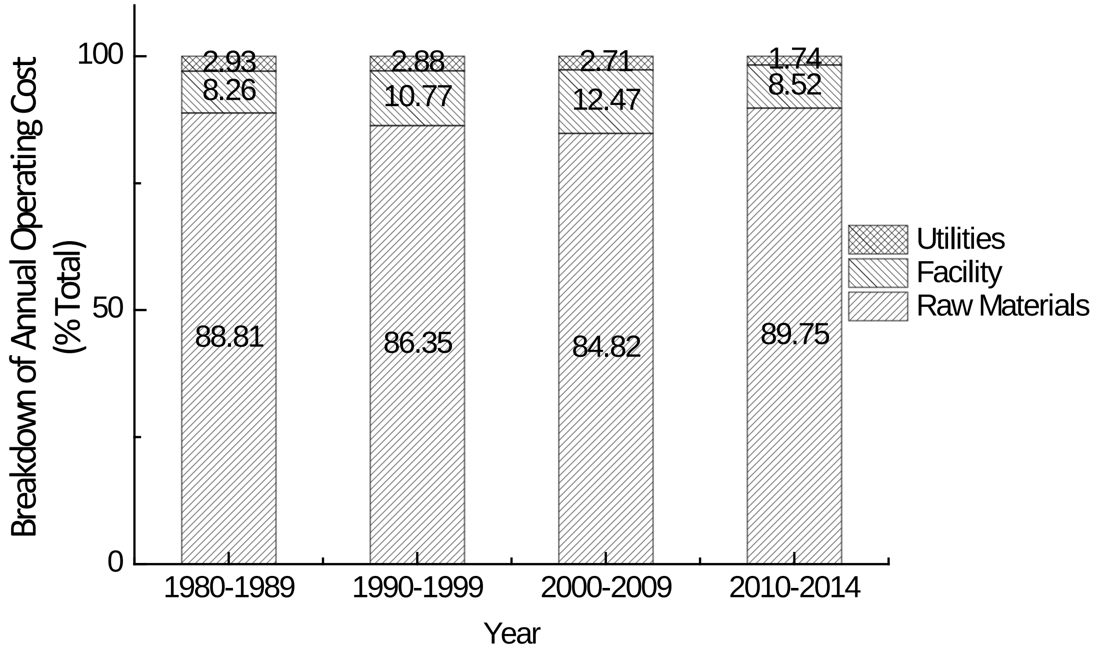

Figure 3 Breakdown of annual operating cost of hexane extraction process

I. Material Costs

In the extraction process, hexane is the only chemical used in the production stream. During the oil degumming process, hot water method was applied. Hence that reduced the cost of chemicals. Otherwise, the hexane was reused with 95% recycle rate during the extraction process. Hence, that also reduced the annual consumption, and saved the operating costs as well. The main materials in whole system were soybean and hexane, their annual amount were 192.28 and 1.15 million kg respectively. For estimating the material costs, the fluctuation of material prices are needed to be considered. From the annual amount of materials used in the process, soybean has over 99% of total materials distribution. The fluctuation of soybean (Figure 4) will contribute the critical factor to the profits of whole production process.

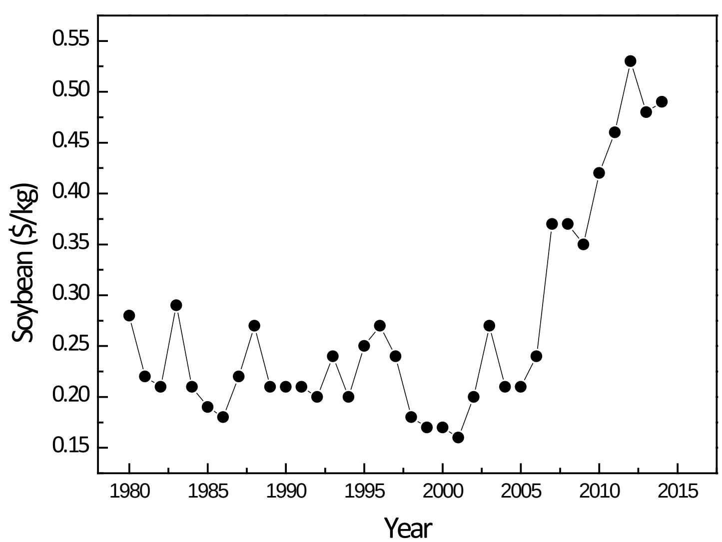

Figure 4 The trend of soybean price from 1980 to 2014 (USDA ERS, 2014)

II. Facility and Utility Costs

Facilities, equipment, are the fundamental requirements for industrial scale production. In operating cost section, that includes maintenance expenses, equipment depreciation, insurance taxes and other miscellaneous fees. In this study, the maintenance fee was set up as 10% of equipment purchasing cost. The facility-dependent operating was from 8% to 12% of total operating costs. That is also relative to the prices of materials, products and energy. For utility cost, that has the smallest contribution in operating costs only taking about not over 3%. According to the results, the influence of facility has been decreased from 1980 to 2014, though the price of electricity has been increased year by year. The large range increase of materials price might be able to explain this condition. In this model, steam and electricity were two main resources of utility costs (Figure 5). Steam was used as the heating source for drying process; electricity was mainly for the rest of units.

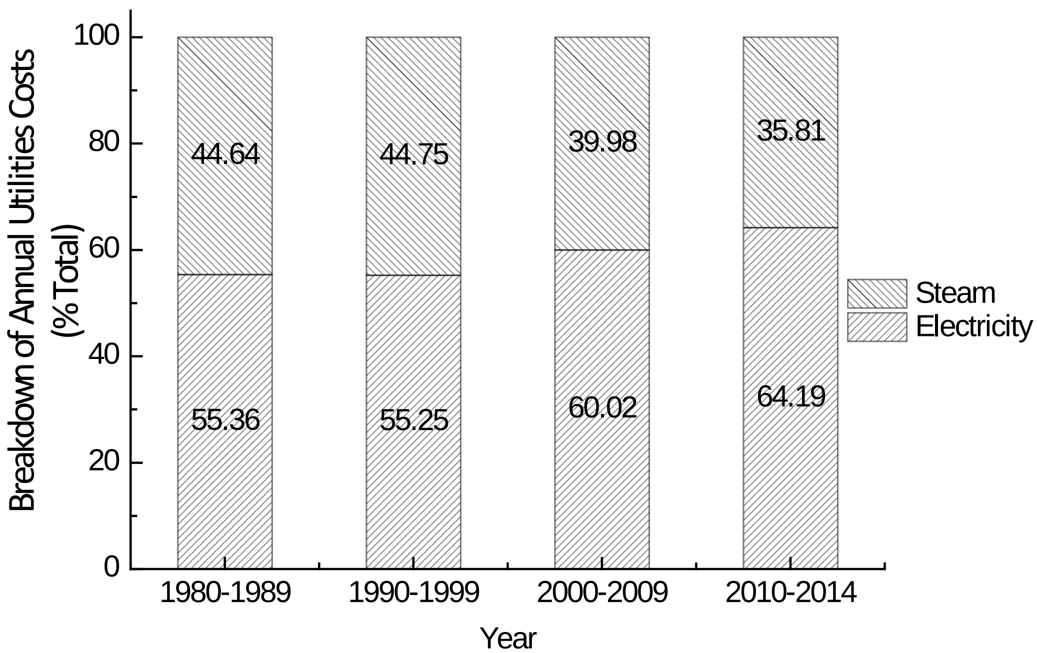

Figure 5 Breakdown utility expenses of annual operating cost

In this model, the price of steam was set as constant of $12/ MT. From the result of utility cost, that also reflects the fluctuation of the price of electricity (Figure6). For whole oil production, the final products will be used as the material of food or animal feeds. When steam was used as the heating resource, the product contamination from the misconduct during any operating unit could be avoided, and also could reduce the operating cost.

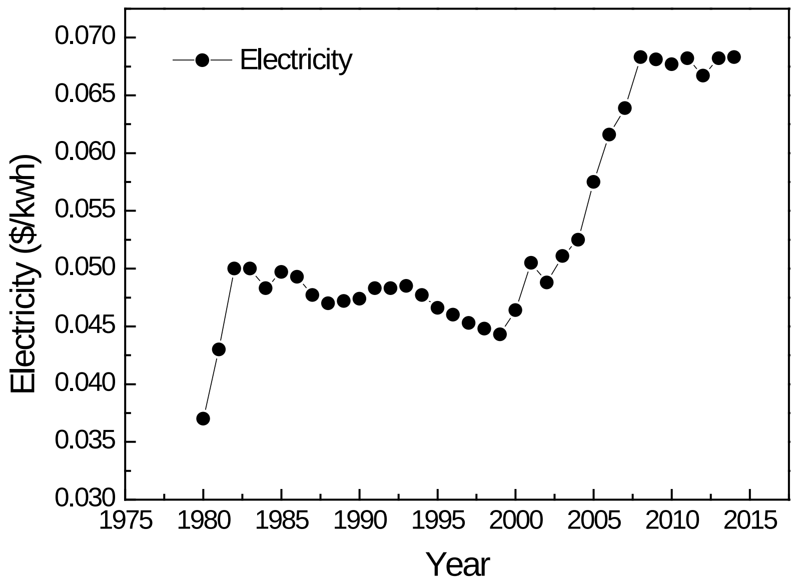

Figure 6 Price of electricity from 1980 to 2014 (EIA, 2014)

Annual Revenues

Soybean oil, soybean meal and soybean hulls are considered as the products of oil extraction process. The prices of these three products from 1980-2014 were used for the economic simulation (Figure 7). According to the results of model simulation, the annual yield of soybean oil, soybean meal and soybean hulls were 33781049 kg, 142445589 kg and 8386489 kg individually. Compared to soybean used as the material, there was about 93% of total material amount going to products. The average annual revenue of 1980-1989, 1990-1999, 2000-2009 and 2010-2014 were $48393933, $48731764, $58986412 and $104685256 separately.

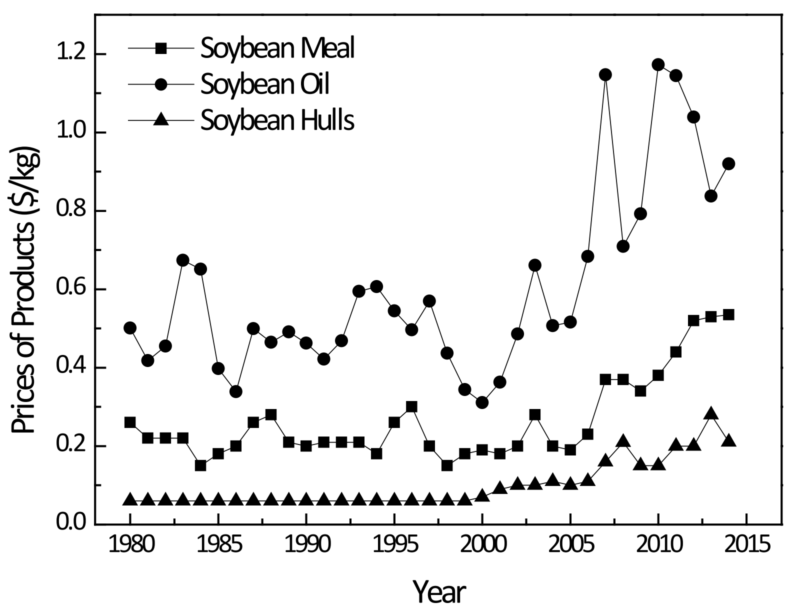

Figure 7 Selling prices of Soybean meal, oil and hulls from 1980 to 2014 (USDA ERS, 2014, Feedstuffs, 1980-2014)

I. Soybean oil

According to the result of simulation, the annual yield of soybean oil is 33781049 kg. The oil content of soybean is 18.57%. During the hexane extraction, the oil extraction rate is about 95%. Based on the average selling prices of soybean oil every 10 years from 1980 to 2014, the average annual revenue from oil of 1980-1989, 1990-1999, 2000-2009 and 2010-2014 are $16552714, $16890524, $20944250 and $34550277individually. The proportion of soybean oil and other co-products are represented in Figure 8.

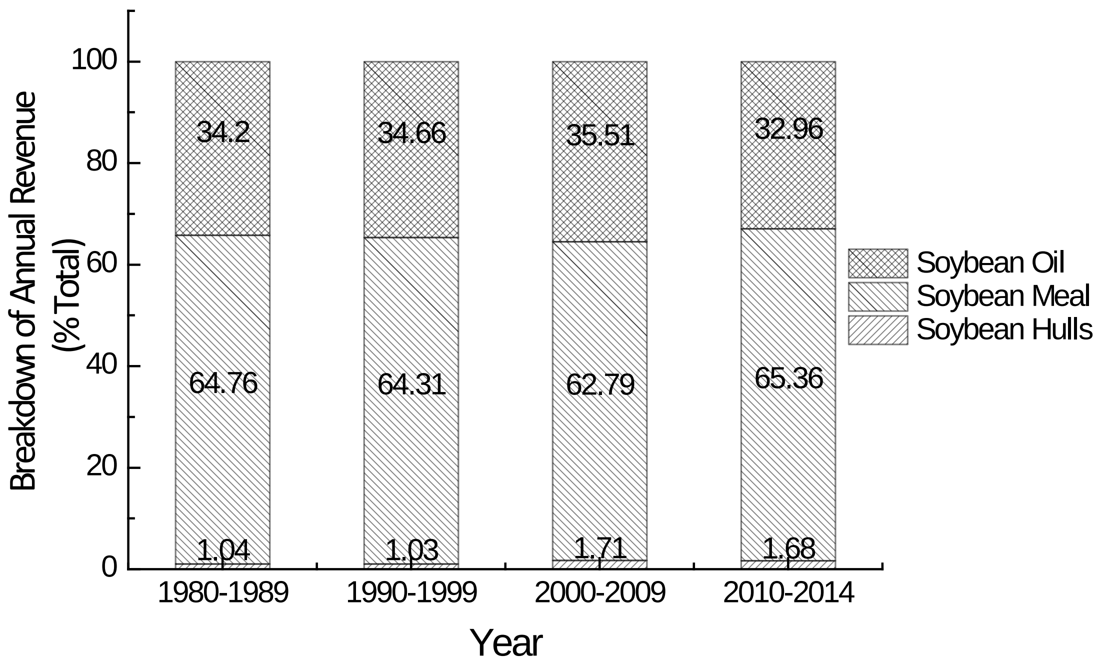

Figure 8 Breakdown of annual revenue from soybeans

From the results, the annual revenue from soybean oil is from 34%-36%. Though soybean oil has the highest unit selling price; however, that only takes about 19% composition of soybean compared to soybean meal of 60%. Hence, that is the reason to explain that soybean oil contributes the revenue followed by soybean meal.

II. Soybean Meal

From Figure 8, the revenue from soybean meal ranges from 62%-66%, and that is also the largest revenue resource in the oil extraction process though that has lower unit selling price followed by soybean oil. This result corresponds to the soybean composition in which soybean meal takes around 60% of whole soybean. The average annual revenue from soybean meal of 1980-1989, 1990-1999, 2000-2009 and 2010-2014 are $31338029, $31338051, $37035783 and $68373816 respectively. This result also reflects the selling price has been increased from 1980 to 2014. Hence, as the soybean meal can be recovered or separated from soybean during the oil extraction process, that could improve the profits significantly.

III. Soybean Hulls

Soybean hulls have the smallest composition of soybean about 7.5%, and that also has the lowest price among these three products. According to Figure 8, soybean hulls provide about 2%-3% of annual total revenues. The average annual revenue from hulls of 1980-1989, 1990-1999, 2000-2009 and 2010-2014 are $503189, $503189, $ 1006379 and $1761163 individually. Thought that is the minor product of the oil extraction, but that is still the good resource for animal feeds because of its high fiber content. Due to the more applications of hull have been noticed especially in animal feeds industry, the hulls production has the potential market in the near future. This condition corresponds to the results from this model simulation as well.

IV. Gross Profits

Gross profit is defined as the difference between annual operating costs and annual revenues. The Figure 9 illustrates the relationship among capital costs, annual operating costs, annual revenues and gross profits.

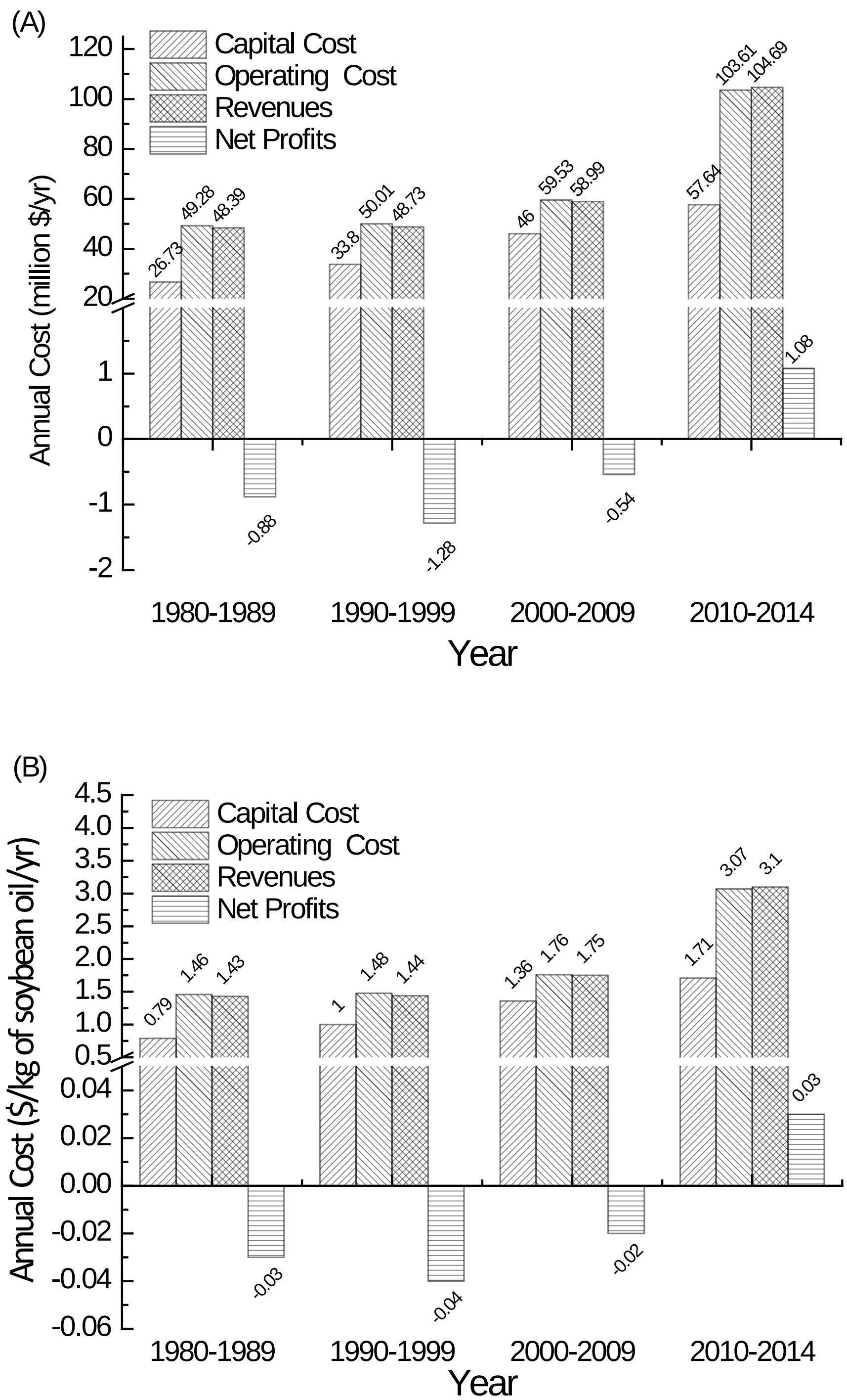

Figure 9 Comparisons of capital cost, operating cost revenues and profits. (A) Cost accumulated for a year of production. (B) Cost per 1 kg of soybean oil production.

From the results, the equipment purchasing prices have been increased from 1980 to 2014 according to the CPI inflation index factor, the costs of material, utilities and operations have also increased year by year depending on the market situation, and economic environment. Hence, the selling price is the key point for determining how much revenues will be. According to Figure 9, the negative annual profits are obtained from 1980-2009 because of low products selling prices and the increase of annual operating cost. Especially from 1990-1999, though the soybean purchasing price was lower than 1980-1989, the selling price of soybean meal also had been decreased and the price of soybean oil had only increased about 1%, that led to the largest negative annual revenues. Additionally, the operating cost had increased as well, those factors made the plant hard to earn profits when the production stream was established before 2010. While the selling prices of products have started getting increased after 2010 with 200% to 300%, the positive revenues could be obtained.

The unit cost and unit gross profits were also conducted based on 1 kg soybean oil production (Figure 9 B). That indicates how much money has to be paid for and earned from 1 kg soybean oil production. From the results, that is corresponding to annual revenues analyses. The unit annual gross profit of 1980-1989, 1990-1999, 2000-2009 and 2010-2014 are $-0.03, $-0.04, $-0.02 and $0.03 for 1 kg soybean oil production separately . These results also indicate that the production stream could earn profits and meet the break-even point as that is built up after 2010.

Additionally, the gross margin and payback time (Table 4) were also calculated. The gross margin is defined as the ratio of the gross profits to revenues. And, the payback time indicates how many years that are needed to earn profits back from production stream. In this simulation, the service time of production stream was set as 15 years. Based on the result, as the production stream was build up before 2000, it was impossible to earn profits; however, it needed to take 14.5 year for earning the profits when the production stream built up between 2000 and 2009. If the plant was established after 2010, that could start to earn money back at the 12th year. Hence, there is the feasibility for oil production with solvent extraction technique if the plant is built up recently.

Table 4 Economic summary of hexane extraction process

	1980-1989	1990-1999	2000-2009	2010-2014
Capital Investment ($)	26731000	33979000	45996000	57639000
Operating Costs ($/yr)	49277000	50010000	59530000	103609000
Revenues ($/yr)	48394000	48732000	58986000	104685000
Gross Profits ($)	-883000	-1278000	-544000	1076000
Gross Margin (%)	-1.82	-2.62	-0.92	1.03
Payback Time (yr)	22.96	23.78	14.42	11.34

Conclusion

The hexane extraction process for soybean oil production includes material handling, oil extraction, meal handling and oil degumming processes. The oil extraction rate is about 95%. From the whole process, the soybean meal has the largest annual revenue contribution about 65% of all revenues because of its highest content in soybean about 60%. Hence, if the soybean meal can be well separated during the oil production process, the revenues can be improved significantly. Otherwise, the increase of selling prices of products is and material costs are more sensitive to other factors because they take the majority impact of the whole production stream. These factors are tightly relative to current market, industrial and economic environment. According to the analysis, the revenues have been increased because the selling prices of products have been increased from 1980-2014. If the production stream was built up after 2000, there is the feasibility to earn the profits. And soybean meal and hulls are the high potential co-products of oil extraction industry.

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