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Enhancing Profitability of Dry Mill Ethanol Plants

Process Modeling and Economics of Conversion of Degermed Defibered Corn to Ethanol

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Abstract

An Aspen Plus™ modeling platform was developed to evaluate the performance of the conversion process of degermed defibered corn (DDC) to ethanol in 15- and 40-million gallons per year (MGPY) dry mill ethanol plants. Upstream corn milling equipment in conventional dry mill ethanol plants was replaced with germ and fiber separation equipment. DDC with higher starch content was fed to the existing saccharification and fermentation units, resulting in higher ethanol productivity than with regular corn. The results of the DDC models were compared with those of conventional dry mill ethanol process models. A simple financial analysis that included capital and operating costs, revenues, earnings, and return on investment was created to evaluate each model comparatively. Case studies were performed on 15- and 40-MGPY base case models with two DDC process designs and DDC with a mechanical oil extraction process.

Index Entries: Dry mill; degermed defibered corn; ethanol; modeling; economics.

Introduction

Annual ethanol production in North America was more than 2.7 billion gallons at the end of 2002 and was expected to grow by 32% in 2003, to 3.56 billion gallons *(1)*. Corn is the major feedstock for ethanol. Two processes are currently used to manufacture ethanol from corn: dry- and wet-milling processes. In the dry-milling process, whole corn is hammer milled

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to the required size followed by liquification, saccharification, fermentation, and downstream separations. The dry-milling process typically yields ethanol, CO_2, and dried distillers grains and solubles (DDGS). In the wet-milling process, corn is steeped for 30–50 h at 120–130°F in dilute sulfur dioxide solution followed by germ, bran, and gluten separations. The resulting starch stream is fermented to ethanol. The wet-milling process typically yields corn oil, germ meal, gluten meal, gluten feed, condensed fermented extractives, starch, and/or ethanol.

Dry mills are less capital intensive but produce less valued byproducts than wet mills. Conversely, profitability in the current wet-milling industry is enhanced by the revenues generated by byproducts. The overall economics of ethanol production in dry mills is expected to improve by designing new plants or modifying existing plants to generate value-added byproducts. Removal of the germ and fiber fractions from the corn enhances the starch concentration in the degermed defibered corn (DDC) and results in higher ethanol productivities during fermentation *(2)*.

Fermentations with DDC increased the ethanol concentration by 11% vs whole corn *(2)*. Several process designs and technologies, such as "Quick Germ" and "Quick Fiber" separations, developed by the University of Illinois, are emerging to fractionate corn into DDC, germ, and fiber *(3,4)*. Several studies have focused on improving dry mill profitability by germ-fiber separation *(4–6)*.

The objective of the present study was to develop an Aspen Plus–based modeling platform to evaluate competing DDC technologies, identify critical cost factors, and provide research directions based on overall process economics. For simplicity, only new corn- and DDC-based dry mill plants were considered. Case studies were performed using feedback from industrial partners, and financial summaries were created to evaluate each model comparatively.

Model Development

Base Case Models

For the base case, 15- and 40-million gallons per year (MGPY) (based on anhydrous ethanol) dry mill models developed by Frank Taylor and colleagues at Eastern Regional Research Center, ARS-USDA (Wyndmoor, PA) were updated in consultation with Delta-T Corporation (DTC), Williamsburg, VA and several industrial collaborators. The production of denatured ethanol (94.9% ethanol) for Base Case 15 and Base Case 40 (MGPY) models were 16.1 and 42.2 MGPY, respectively. The models included process flows and parameters, capital costs, raw materials, utilities and fixed costs, and byproducts revenues. The feedstock consisted of corn with 73 wt% starch on a dry basis. Ethanol concentration in the beer was 10 wt%. Protein concentration in the DDGS was 28 wt%.

As shown in Fig. 1, the unit operations included in the process model are dry milling, cooking-liquification, saccharification, fermentation, dis-

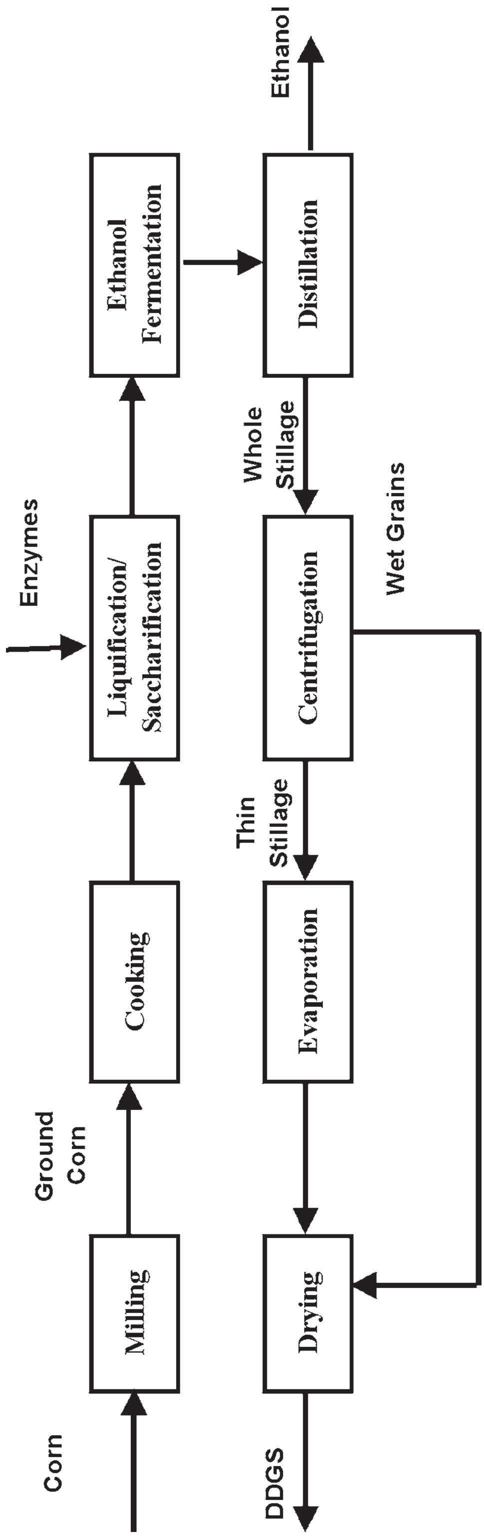

Fig. 1. Process flow diagram for base case ethanol model.

Table 1
Design Basis for Base Case Model

Parameter	Value
Starch to glucose efficiency	98%
Glucose to ethanol efficiency	93%
Beer concentration	10% by wt.
Centrifuge efficiency	78%
Wet cake solids	35%
Syrup solids	40%
DDGS moisture	10%
Operating hours	8400 h/yr
Denaturant in product	4.76%
Thermal oxidizer	Included
Boiler efficiency	82%

tillation, molecular sieve separation, stillage concentration, and DDGS separation. Utilities used by the process include steam, gas, electricity, chilled/cool water, and cooling tower water.

Steam was generated on-site using a gas-fired boiler. The cost for cooling tower water is assumed to be zero owing to the availability of on-site cooling tower water. Steam cost was transferred to natural gas cost in the boiler with 82% efficiency. Centrifuge efficiency was 78% and wet cake solid content was 35% based on DTC feedback. The design basis for the base case model is provided in Table 1.

DDC Models

Upstream corn-milling equipment in 15- and 40-MGPY base case models was replaced with the germ and fiber separation equipment shown in Fig. 2. The unit operations included in the integrated process were corn cleaning, germ and fiber separation, germ and fiber drying, cooking-liquification, saccharification, fermentation, distillation, molecular sieve separation, stillage concentration, and DDGS separation. DDC with higher starch content was fed to the existing saccharification and fermentation units, resulting in higher ethanol productivity than with regular corn. The mass flow rates of mash were made comparable to the base case model by adjusting the water balance in the model. DDC streams generated by two technologies—(1) Frazier Barnes Associates and CTI Technology (FB) based on a 1993 patent *(7)*, and (2) DTC—were used for the analysis. The DTC-DDC 15 (MGPY) model generated DDC, fiber, and germ with 79, 68, and 40 wt% starch (dry basis), respectively. Beer ethanol concentration was 10.7 wt%. The FB-DDC 15 and 40 (MGPY) designs generated DDC, fiber, and germ with 86, 25, and 25 wt% starch (dry basis), respectively. Beer ethanol concentration was 10.8 wt%. Additionally, the centrifuge efficiency was reduced to 75%, and wet cake solid content was reduced to 35% based on DTC feedback.

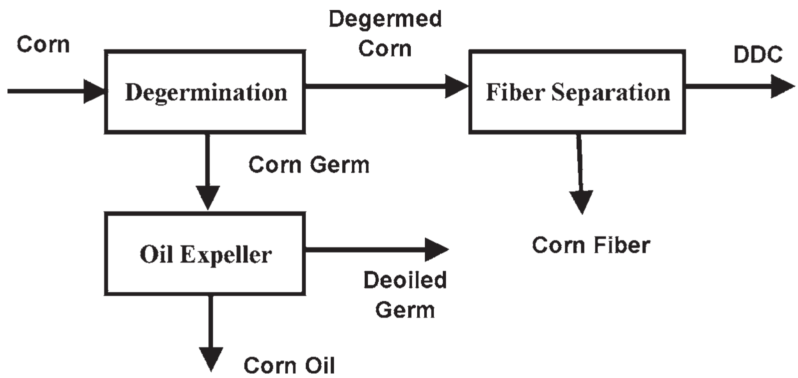

Fig. 2. Process for corn fractionation in DDC models.

Table 2
Market-Sensitive Assumptions

	Unit	Price/unit
Ethanol	Gal	$1.24
Corn	Bu	$2.38
Gas	MMBtu	$5.00
Electricity	kWh	$0.05
DDGS	US ton	$95.25
Hi-DDGS	US ton	$110.00
Corn germ	US ton	$131.00
Corn fiber	US ton	$60.00
Corn oil	US ton	$520.00
De-oiled germ	US ton	$110.00
α-Amylase	lb	$1.50
Glucoamylase	lb	$1.50
Yeast	lb	$2.50

DDC Model With Oil Extraction

As a special case, the FB-DDC 40 model was expanded to include a mechanical oil expeller block. The efficiency of the mechanical expeller was assumed to be 63%. The remaining oil was retained in the de-oiled germ stream without actually enhancing its value.

Economic Models

The mass and energy balance results generated by the base case and DDC models were exported to a separate spreadsheet to evaluate the process economics. Equipment and utilities costs were updated by DTC. A straight-line annual depreciation for 10 yr of project life was assumed. No salvage value was considered at the end of the project life. The price of ethanol, corn, and other market-sensitive assumptions are provided in Table 2. These prices were reviewed and updated by industrial collaborators. The DDC-DDGS, also known as Hi-DDGS, from DDC process is priced at $110/t owing to the expected increase in protein content. Germ value is set at $131/t based on current oil price and processing costs. Germ value was updated by MBI based on feedback from Frazier-Barnes Associates. Fixed operating costs were updated by the industrial partners listed under Acknowledgments.

Results and Discussion

Ethanol Production

With the DTC-DDC 15 design, annual production rate was enhanced from 16.1 to 17.7 MGPY of denatured ethanol. The FB-DDC 15 design increased the production rate from 16.1 to 17.9 MGPY, and the FB-DDC 40 design increased the production rate from 42.2 to 47.1 MGPY. Germ and fiber separation from corn resulted in a DDC stream higher in starch content than corn. Even at comparable solid loadings, DDC mash had a higher starch concentration and a lower fiber concentration than corn mash. The net result was an increase in ethanol productivity (lb of ethanol/cu ft-h) in DDC fermentations compared to the base case.

Ethanol and DDGS Yields

The base case ethanol yield was 2.74 dry gal/bu and DDGS yield was 18.1 lb/bu for both the 15- and 40-MGPY plants. With the DTC-DDC 15, overall ethanol yield dropped to 2.1 dry gal/bu. Ethanol production increased by 10% over the base case. However, corn utilization increased by 44%, resulting in lower overall yields. DDGS yield was 11 lb/bu of corn. With the FB-DDC 15 and 40, overall ethanol yield 2.63 dry gal/bu and DDGS yield was 10 lb/bu. Ethanol production increased by 11% over the base case and corn utilization increased by 13.6% over the base case. Starch losses in germ and fiber streams owing to separation inefficiencies in DDC plants resulted in a lower yield of ethanol per bushel of corn. Net DDC-DDGS yields (lb/bu) were lower owing to the removal of fiber and germ components from corn. However, proteins were concentrated in the DDC stream, and the protein content of DDC-DDGS was higher, at 35%, compared with 26% in corn-based DDGS.

Germ and Fiber Yields

The DTC-DDC 15 model generated 4.7 lb of corn germ/bu and 9.6 lb of fiber/bu. Based on Frazier Barnes germ and fiber separation efficiencies, the FB-DTC 15 and 40 models generated 5.36 lb of germ/bu and 3.56 lb of fiber/bu.

Utilities

The base case plants utilized electricity at 1 kWh/dry gal and natural gas at 0.035 MMBtu/dry gal. With added energy loads in the DDC process, electricity usage increased to 1.1 kWh/dry gal, and the gas usage increased to 0.036 MMBtu/dry gal. For the oil recovery equipment, incremental costs were added as electricity costs at 0.336 kWh/dry gal of ethanol.

Capital and Fixed Costs

The total capital was $29.8 million for Base Case 15 and $52 million for Base Case 40 models, representing $1.85/gal and $1.23/gal, respectively. The total capital was estimated at $35.8 million for both DDC 15 models. For the FB-DDC 40 model, the estimated capital was $59 million, with an additional $3.2 million for oil recovery. Labor and other fixed costs were updated using feedback from industrial collaborators.

Financial Summaries

The economic performances of the various models considered for the study were compared using return on investment (ROI) financial analysis as shown in Table 3.

Base Case 15

Total operating costs excluding byproduct credits were $23 million/yr. Revenue from sales was estimated at $19.96 million/yr from ethanol and $4.8 million/yr from DDGS. The earnings before interest and income tax (EBIT) was $1.7 million/yr, and the earnings before interest, income tax, depreciation, and amortization (EBITDA) was $4.35 million/yr.

Base Case 40

Total operating costs excluding byproduct credits were $56 million/yr. Revenue from sales was estimated at $52.36 million/yr from ethanol and $12.58 million/yr from DDGS. The EBIT was $9 million/yr and the EBITDA was $13.73 million/yr. Improved economy of scale leading to lower capital, labor, and depreciation per gallon of ethanol enhanced the overall economy of the 40-MGPY plant.

DTC-DDC 15

Total operating costs excluding byproduct credits were $30.9 million/yr. Revenue from sales was estimated at $21.90 million/yr from ethanol, $4.85 million/yr from DDGS, $2.48 million/yr from dry germ, and $2.30 million/yr from dry fiber. The EBIT was $578,351/yr and the EBITDA was $3.77 million/yr. Low ethanol yields resulted in higher corn demand and costs. The overall increase in operational costs overshadowed improvements in ethanol productivity and product revenues. Net drop in EBIT and added cost of DDC separation equipment resulted in unattractive returns compared to the Base Case 15 model.

FB-DDC 15

Total operating costs excluding byproduct credits were $26.3 million/yr. Revenue from sales was estimated at $22.25 million/yr from ethanol, $3.6 million/yr from DDGS, $1.9 million/yr from dry germ, and $0.6 mil-

Table 3
Financial Summaries

	DDC project (denatured ethanol capacity [MGPY])					
	FB-DDC 40 with oil (47.1)	FB-DDC 40 (47.1)	Base Case 40 (42.2)	FB-DDC 15 (17.9)	DTC-DDC 15 (17.7)	Base Case 15 (16.1)
Construction costs						
Equipment	$19,049,058	$18,049,058	$16,006,558	$10,734,678	$10,734,678	$9,406,023
Installation	$32,968,546	$30,768,546	$25,809,646	$15,591,837	$15,591,837	$12,231,091
Engineering/supervision	$2,200,000	$2,200,000	$2,200,000	$2,070,000	$2,070,000	$1,800,000
Land preparation	$625,000	$625,000	$625,000	$625,000	$625,000	$535,002
General construction	$1,600,000	$1,600,000	$1,600,000	$1,600,000	$1,600,000	$1,300,000
Fees/licenses	$700,000	$700,000	$700,000	$639,800	$639,800	$545,698
Contingency	$865,000	$865,000	$865,000	$663,672	$663,672	$572,000
Total construction costs	$58,007,604	$54,807,604	$47,806,204	$31,924,986	$31,924,986	$26,389,814
Other capital costs						
Land cost	$125,000	$125,000	$125,000	$100,000	$100,000	$100,000
Start-up costs	$800,000	$800,000	$800,000	$800,000	$800,000	$687,587
Start-up inventory	$800,000	$800,000	$800,000	$740,113	$740,113	$605,999
Working capital	$2,500,000	$2,500,000	$2,500,000	$2,243,924	$2,243,924	$2,025,714
Total capital costs	$4,225,000	$4,225,000	$4,225,000	$3,884,037	$3,884,037	$3,419,300
Total capital	$62,232,604	$59,032,604	$52,031,204	$35,809,023	$35,809,023	$29,809,114

Projected statement of earnings						
Sales						
Ethanol ($1.24/gal)	$58,361,505	$58,361,505	$52,364,514	$22,247,034	$21,896,135	$19,957,626
DDGS ($95/t)			$12,582,932			$4,796,204
DDC-DDGS ($110/t)	$9,275,406	$9,275,406		$3,631,541	$4,846,347	
Corn oil ($0.26/lb)	$3,801,390					
Corn germ ($131/t)		$5,952,460		$1,899,857	$2,457,925	
De-oiled germ ($110/t)	$4,194,873					
Corn fiber ($60/t)	$1,808,252	$1,808,252		$611,226	$2,302,544	
Total sales	$77,441,426	$75,397,624	$64,947,446	$28,389,658	$31,502,951	$24,753,830
Production and operating expenses						
Feedstock ($2.38/bu)	$40,248,464	$40,248,464	$34,672,452	$15,020,561	$19,013,008	$13,215,320
Other raw materials	$4,889,678	$4,889,678	$4,178,848	$1,836,451	$2,144,555	$1,592,759
Utilities	$11,402,118	$10,651,216	$9,472,216	$3,794,355	$4,128,688	$3,442,088
Labor, supplies, and overhead	$3,017,888	$2,950,519	$2,896,756	$2,445,850	$2,445,850	$2,150,350
Depreciation	$5,800,760	$5,480,760	$4,780,620	$3,192,499	$3,192,499	$2,638,981
Total production costs	$65,358,908	$64,220,637	$56,000,891	$26,289,716	$30,924,600	$23,039,498
Income						
EBIT	$12,082,518	$11,176,987	$8,946,554	$2,099,942	$578,351	$1,714,332
EBITDA	$17,883,279	$16,657,747	$13,727,174	$5,292,441	$3,770,850	$4,353,314
ROI (EBIT/total capital)	19.42%	18.93%	17.19%	5.86%	1.62%	5.75%

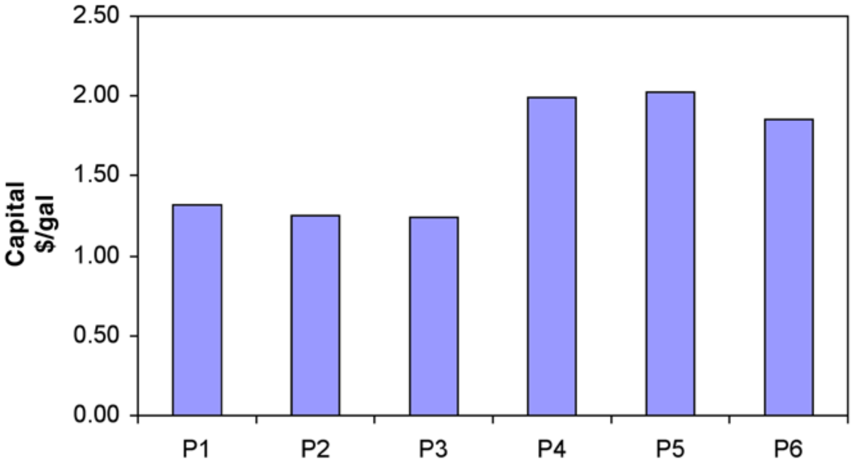

Fig. 3. Capital cost per gallon of ethanol: P1 = FB-DDC 40 with oil, P2 = FB-DDC 40, P3 = Base Case 40, P4 = FB-DDC 15, P5 = DTC-DDC 15, P6 = Base Case 15.

lion/yr from dry fiber. The EBIT was $2.1 million/yr and the EBITDA was $5.3 million/yr. Improvement in germ-fiber separation efficiency significantly enhanced FB-DDC 15 economics over the DTC-DDC 15 model.

FB-DDC 40

Total operating costs excluding byproduct credits were $64.2 million/yr. Revenue from sales was estimated at $58.4 million/yr from ethanol, $9.3 million/yr from DDGS, $6.0 million/yr from dry germ, and $1.8 million/yr from dry fiber. The EBIT was $11.2 million/yr and the EBITDA was $16.7 million/yr.

FB-DDC 40 With Oil

Total operating costs excluding byproduct credits were $65.4 million/yr. Revenue from sales was estimated at $58.4 million/yr from ethanol, $9.3 million/yr from DDGS, $4.2 million/yr from de-oiled germ, $3.8 million/yr from oil, and $1.8 million/yr from dry fiber. The EBIT was $12.1 million/yr and the EBITDA was $17.9 million/yr.

FB-DDC 40 models benefited from improvements in germ-fiber separation efficiency, economy of scale and value-added byproducts over the base case and the DTC-DDC model.

As shown in Fig. 3, the capital cost/gal of ethanol depended on the plant size. The base case plants required $1.85/gal and $1.23/gal at the 15- and 40-MGPY scales, respectively. The DTC and FB-DDC 15 plants required capital at $2/gal. The FB-DDC 40 model required marginally higher capital than the base case. Oil recovery increased the capital intensity by $0.09/gal over the base case.

As shown in Fig. 4, the economy of scale affects the production cost of ethanol. Ethanol production costs (including byproduct revenues) were $1.13/gal for the Base Case 15 model and $1.03 for the Base Case 40 model.

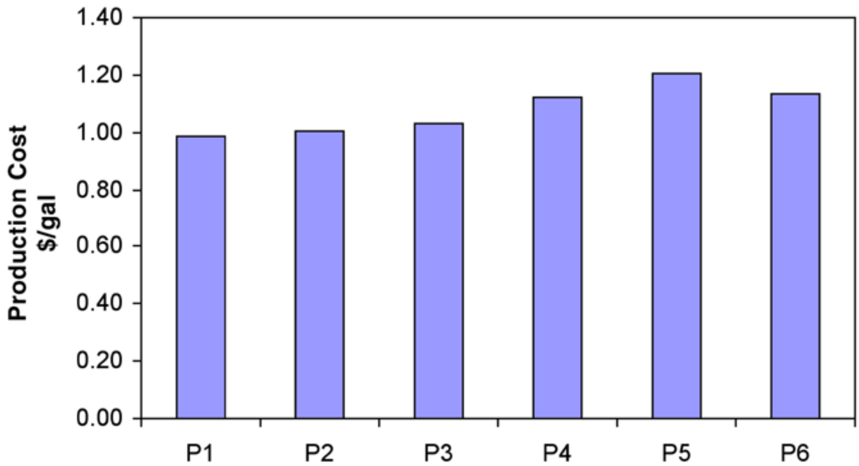

Fig. 4. Production cost per gallon of ethanol: P1 = FB-DDC 40 with oil, P2 = FB-DDC 40, P3 = Base Case 40, P4 = FB-DDC 15, P5 = DTC-DDC 15, P6 = Base Case 15.

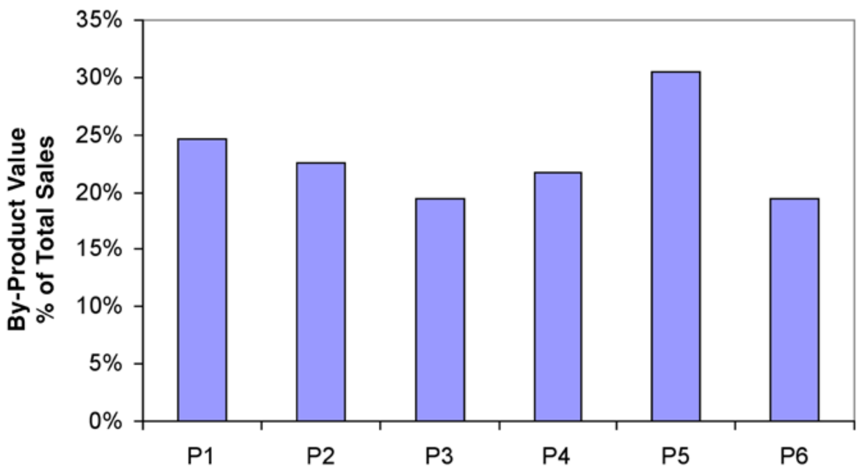

Fig. 5. Byproduct revenue contribution to total sales: P1 = FB-DDC 40 with oil, P2 = FB-DDC 40, P3 = Base Case 40, P4 = FB-DDC 15, P5 = DTC-DDC 15, P6 = Base Case 15.

The DTC-DDC 15 model projected an increase of $0.07/gal over the base case. Owing to the improvement in separation efficiencies and reduced starch losses in germ and fiber streams, the FB-DDC 15 model predicted a reduction of $0.01/gal over the base case. The FB-DDC 40 model lowered the production costs by $0.03/gal, and the FB-DDC 40 with oil model reduced the cost by $0.05/gal over the base case.

The revenue contribution from byproducts was significant in the DTC-DDC 15 model as shown in Fig. 5. Byproducts accounted for 30.5% of the total sales compared with 19.4% in the Base Case 15 model. The FB-DDC 15

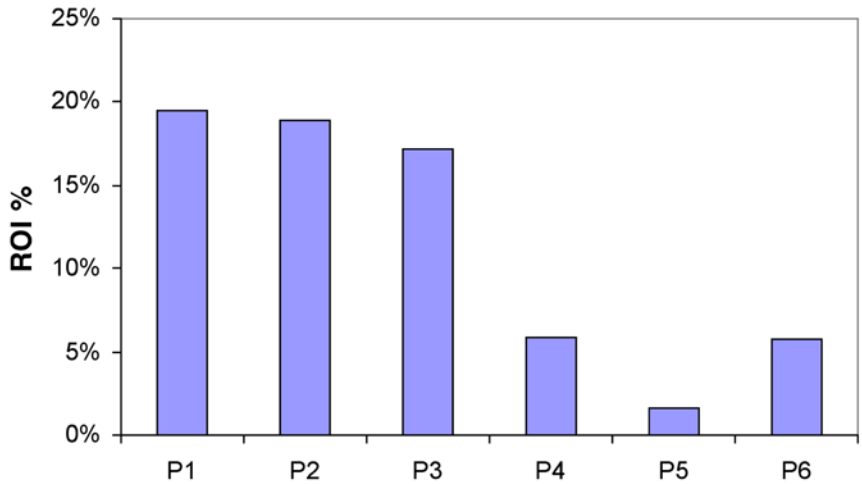

Fig. 6. ROI: P1 = FB-DDC 40 with oil, P2 = FB-DDC 40, P3 = Base Case 40, P4 = FB-DDC 15, P5 = DTC-DDC 15, P6 = Base Case 15.

and 40 models showed a marginal increase over the base case. However, oil recovery increased the byproduct revenue by 5.3% over the base case.

ROI, defined as the ratio of EBIT over total capital, for each case is compared in Fig. 6. The DTC-DDC 15 model was less attractive (ROI = 1.62%) than the Base Case 15 model (ROI = 5.75%). The FB-DDC 15 model marginally improved the ROI over the base case. However, at the 40-MGPY scale, the FB-DDC 40 models showed a 1.74% (without oil) and 2.23% (with oil) increase in ROI over the base case.

Sensitivity Analysis

The effect of market-sensitive parameters on the overall performance of each model is shown in Table 4. Current economic models (case 1) were based on the assumptions in Table 2. For case 2, the prices were changed to \$1.18/gal of ethanol, \$85/t of DDGS, \$100/t of DDC-DDGS, and \$2.2/bu of corn to represent a specific industrial condition. Individual ROIs decreased for all the cases, as shown in Table 4. However, the overall trend in ROI was not affected. Case 3 is an extension of case 1 with the germ value dropped to \$80/t. The sensitivity of the DDC models to changes in germ value is evidently illustrated. As shown in Table 4, the production costs of ethanol increased and ROIs decreased for all DDC models with the exception of the oil recovery case.

Based on this study, we have identified several internal and external cost factors influencing the overall performance of DDC plants. External factors included market prices of corn, DDGS, ethanol, and other byproducts. Lower corn prices and higher ethanol, corn oil, de-oiled germ, DDC-DDGS, and fiber prices would favor DDC plants over existing ethanol plants. Internal cost factors were influenced by plant scale, germ-fiber sepa-

Table 4
Effect of Market-Sensitive Parameters

	DDC project (denatured ethanol capacity [MGPY])					
	FB-DDC 40 with oil (47.1)	FB-DDC 40 (47.1)	Base Case 40 (42.2)	FB-DDC 15 (17.9)	DTC-DDC 15 (17.7)	Base Case 15 (16.1)
Case 1						
Capital cost ($/gal)	$1.32	$1.25	$1.23	$2.00	$2.02	$1.85
Production cost ($/gal)	$0.98	$1.00	$1.03	$1.12	$1.20	$1.13
Byproduct sales	24.64%	22.60%	19.37%	21.64%	30.49%	19.38%
ROI	19.42%	18.93%	17.19%	5.86%	1.62%	5.75%
Case 2						
Capital cost ($/gal)	$1.32	$1.25	$1.23	$2.00	$2.02	$1.85
Production cost ($/gal)	$0.94	$0.96	$1.00	$1.08	$1.15	$1.10
Byproduct sales	24.72%	22.57%	18.43%	21.54%	30.55%	18.43%
ROI	18.41%	17.88%	14.82%	5.11%	1.44%	4.17%
Case 3						
Capital cost ($/gal)	$1.32	$1.25	$1.23	$2.00	$2.02	$1.85
Production cost ($/gal)	$0.98	$1.05	$1.03	$1.16	$1.26	$1.13
Byproduct sales	24.64%	20.14%	19.37%	19.54%	28.32%	19.38%
ROI	19.42%	15.01%	17.19%	3.80%	–1.06%	5.75%

ration efficiency, and starch losses in the DDC processes. Higher-scale operation and improvements in process design leading to lower starch losses in germ and fiber streams will enhance DDC process economics over existing ethanol plants.

Conclusion

An Aspen Plus modeling platform was developed to evaluate the performance of DDC to ethanol conversion in 15- and 40-MGPY dry mill ethanol plants. Financial summaries were generated to compare the economics of corn- and DDC-based dry mill ethanol plants. Case studies were performed using different DDC process designs and feedback from industrial partners. Germ-fiber separation efficiency, starch loss in germ-fiber streams, and market values of the byproducts were established as critical factors affecting the overall economics of the DDC process. Additionally, the economies of scale and oil recovery at 40-MGPY capacity were established as important factors enhancing the profitability of DDC plants over conventional dry mill ethanol plants. Future research in this area should focus on improving equipment design for efficient germ-fiber separation and reduced capital requirement; enhancing oil recovery from germ; and developing value-added products from corn fiber, de-oiled germ, and DDGS.

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