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Profit Maximization in Ethanol Production (May 2007)

R. Sriram, S. Subramanian, and G. Tomlin

Abstract - **We document an experimental study to optimize yield of an ethanol distillation process. The yield is expressed in terms of concentration of the ethanol obtained, and the profit from the process. Concentration is a function of six input factors that can be varied within a given range. Profit is a function of the revenue (which depends on the concentration of ethanol achieved) and costs (which vary with the input factor settings).**

We started by determining a practical operating range for the six input parameters where the constraints of the system (pressure in the distillation column and holding tanks) were not violated. We then conducted a factorial experimental analysis and used a response surface method (path of steepest ascent) to determine an operating point where the desired concentration level is achieved. Finally, we used a space filling experimental design in a narrow region around the operating point to determine the effect of various input parameters on robustness and profit.

Index Terms—**Ethanol, Design of Experiments, Optimization**

I. PROBLEM DEFINITION

Our team found a distillation simulator [2] that was used as the basis of a project at Virginia Tech. This simulator can be found at www.stat.vt.edu/~vining. The simulator takes an input of 6 factors and gives outputs of concentration, profit and pressure. The objective is to maximize profit by changing the six factors.

The six factors are:
  Feed Rate   (gallons per minute)
  Feed Temperature   (Fahrenheit)
  Distillate Rate   (gallons per minute)
  Condensate Temperature   (Fahrenheit)
  Reboil Temperature   (Fahrenheit)
  Reflux ratio   (percent)

Having no knowledge of the operating conditions, we were provided with costs, revenues, and constraints. This gave us a basic understanding of the premise, and we were able to use given pilot values as a starting point for our analysis.

The given costs are:
  Fixed Costs $1,000 per run
  Heating Costs $0.08 / 100,000 Btu
  Cooling Costs $0.04 / 100,000 Btu
  Raw Material Costs $0.015 / gallon

The given revenue is:
	concentration	< 80%	= $ 0
80%<	concentration	< 90%	= $ .50/gallon
90%<	concentration	< 95%	= $1.00/gallon
95%<	concentration	< 100%	= $1.25/gallon

Constraints given are pressure limits. If maximum pressure is exceeded then the process fails, no product is made and repair costs are extraordinary.

II. EXPERIMENTS/DATA

A. Determining operating range for experimental factors

As described earlier, the ethanol-water distillation column has six factors that can be adjusted. The setting for each factor has a large range. However, every setting for each parameter is not likely to produce ethanol, as some settings would violate the constraints of the system (Eg: Pressure constraint of the holding tank and the pressure constraint of the distillation column).

In order to determine the operating range (Figure 1) for each factor setting we varied one factor at a time (OFAT). We took the pilot settings as the starting point and fixed all but one factor at the pilot setting and varied the one factor over its entire settings range. This process was repeated for each factor one at a time. This approach ignored any interaction effects that might exist between the different factors. Based on this analysis the operating range for each factor was determined. The following chart illustrates the operating range and the pilot setting for each parameter.
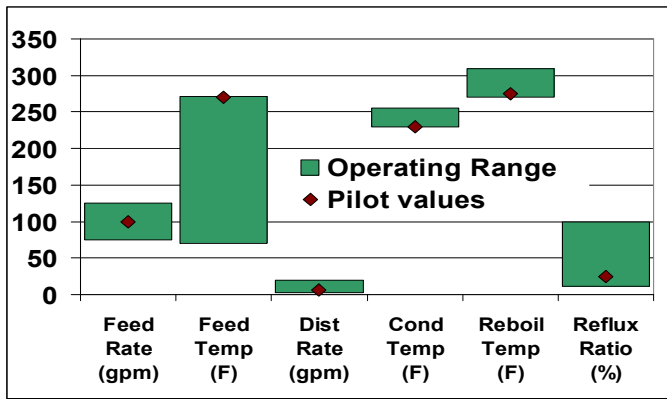
Figure 1. Operating range of simulator with pilot values

B. Full factorial experiment within operating range

Having determined the operating range, a 2-level full factorial experiment was run within half the operating range with the mid-point of the operating range as the mid-point of the experiment.

Figure 2 shows the range for the full-factorial experiment. The white line in the figure shows the actual range over which the experiment was performed.
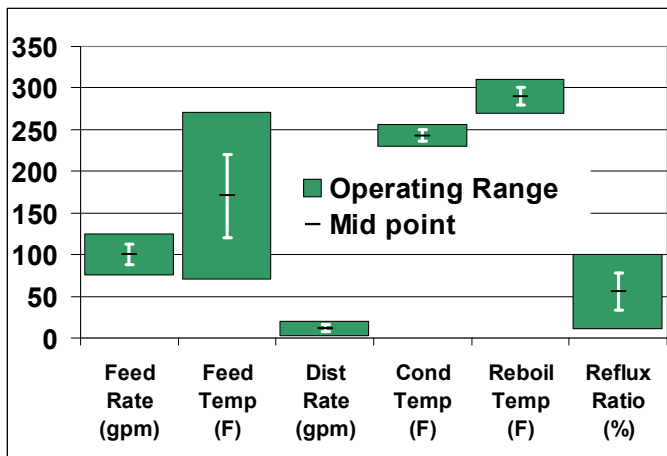

Figure 2. Operating range of simulator with test ranges

The results of the full factorial experiment were analyzed in JMP to determine the significant factors. The first step of the analysis considered all 6 six factors with main effects and 2 way interactions. Higher order terms were ignored. This first step of the analysis was performed to determine which factors were significant.

The above analysis resulted in three significant factors. The data was then further analyzed in JMP with just these three factors and all interactions including 3 way interactions. The results of this analysis are given in the Figure 3.

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	0.471875	0.017487	26.98	<.0001*
Dist Rate	−0.143125	0.017487	−8.18	<.0001*
Cond Temp	−0.054688	0.017487	−3.13	0.0028*
Dist Rate*Cond Temp	0.0546875	0.017487	3.13	0.0028*
Reflux Ratio	−0.040313	0.017487	−2.31	0.0249*
Dist Rate*Reflux Ratio	0.0090625	0.017487	0.52	0.6063
Cond Temp*Reflux Ratio	−0.053125	0.017487	−3.04	0.0036*
Dist Rate*Cond Temp*Reflux Ratio	0.053125	0.017487	3.04	0.0036*

Figure 3. Parameter Estimates

Some non-random residuals indicate that the behavior model may need to be enhanced to include curvature parameters. (Figure 4)
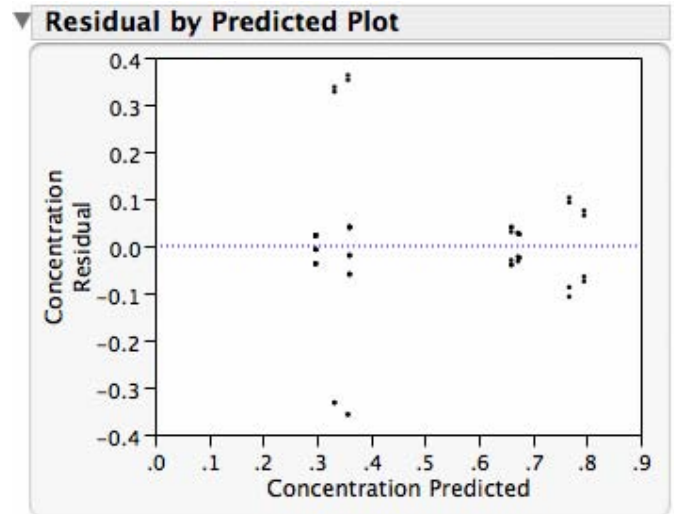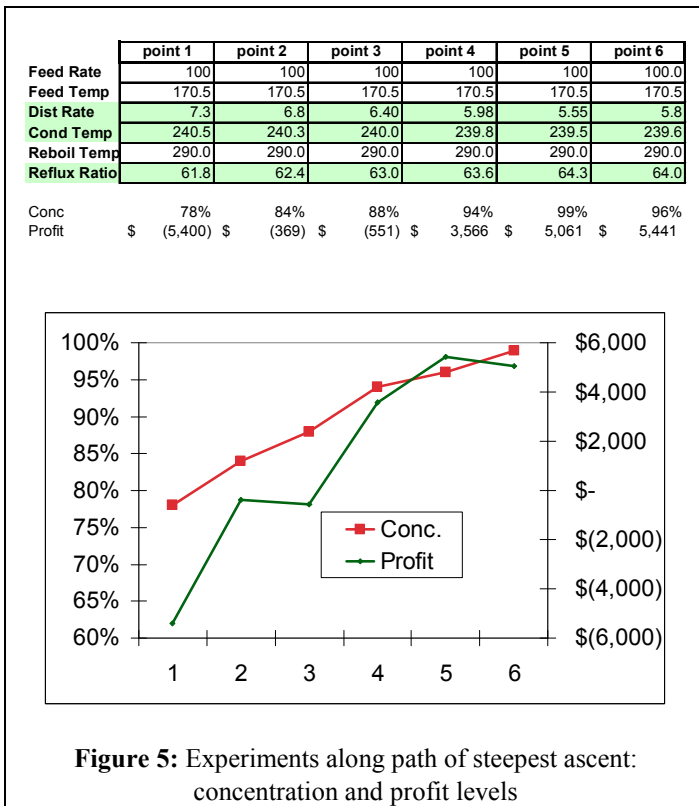

Figure 4. Residuals as function of concentration predicted

III. ANALYSIS

A. Concentration Optimization

From the table of effects from the experiment above, we see that the three factors that are significant are Distillate Rate, Condensate Temperature, and Reflux Ratio. The sign of the significant effects suggests that in order to maximize concentration, we should set all three of these factors at their low values, and then further decrease them along the path of steepest ascent. However, if we do this, we see that the significant two way interactions have the opposite sign that counteracts the increase in concentration. Hence we see that to increase concentration, we should actually set the Reflux Ratio high, and continue to increase this factor.

Having determined that the Distillate Rate and Condensate Temperature should be decreased, and the Reflux Ratio should be increased, we determined the path of ascent using the ratios of the main effects of these factors. We then moved along this path by decreasing the Distillate Rate by 0.1 coded units at a time (equivalent to a 0.425 GPM decrease in real units), and changed the other two variables proportionally. This path resulted in the experiments shown in Figure 5. As seen, the concentration values increased and reached 94% by the fourth experiment. At this point, we reduced the step to 0.05 coded units, and performed two more experiments. We saw that the concentration continued to increase, first to 96% and then to 99%. However, we noticed that the profit was highest at the 96% concentration level, and dropped off at the 99% level. This makes sense, since the underlying revenue function yields the same revenue per gallon for any concentration above 95%, while the costs increase to reach higher concentration levels. Based on this result, we concluded that a good operating point would be the experiment that yielded 96% concentration.

	point 1	point 2	point 3	point 4	point 5	point 6
Feed Rate	100	100	100	100	100	100.0
Feed Temp	170.5	170.5	170.5	170.5	170.5	170.5
Dist Rate	7.3	6.8	6.40	5.98	5.55	5.8
Cond Temp	240.5	240.3	240.0	239.8	239.5	239.6
Reboil Temp	290.0	290.0	290.0	290.0	290.0	290.0
Reflux Ratio	61.8	62.4	63.0	63.6	64.3	64.0
Conc	78%	84%	88%	94%	99%	96%
Profit	$ (5,400)	$ (369)	$ (551)	$ 3,566	$ 5,061	$ 5,441

Figure 5: Experiments along path of steepest ascent: concentration and profit levels

B. Profit Optimization

Having arrived at an operating point that yielded the desired concentration level, our next step was to explore the region around this operating point. There were two main reasons for this: (a) we wanted to make sure that the operating point was robust, i.e. a slight change in the factors would not result in slipping below the 95% concentration level with a dramatic loss in profit, and (b) we wanted to determine the effect of factor changes on profit, to maximize profit.

We conducted a Latin Hypercube space filling experiment in a +/-2% range around the operating point. A total of 64 experiments were conducted. The results for concentration and profit level are shown in the 3-D plots below, which are coded by color level. The results show the highly non-linear behavior of the concentration and profit functions. In fact, even in this narrow 2% range of variation, a few treatment points resulted in a negative profit since the pressure limits were exceeded and the experiment failed.

Figure 6 and 7 show the level of concentration and profit response at a given level of the 3 input factors. The color indicates the level of the output.

Figure 8 shows a sliced contour [profit vs. reflux ratio] at a certain level of distillate rate and condensate temperature. The step function nature of profit is clearly seen in this figure.
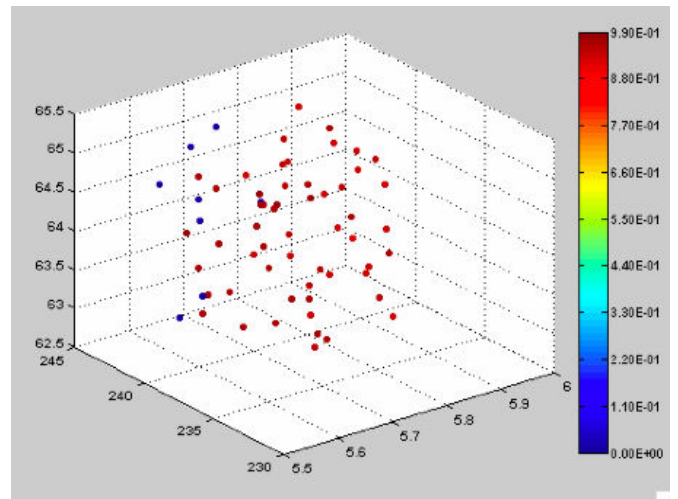

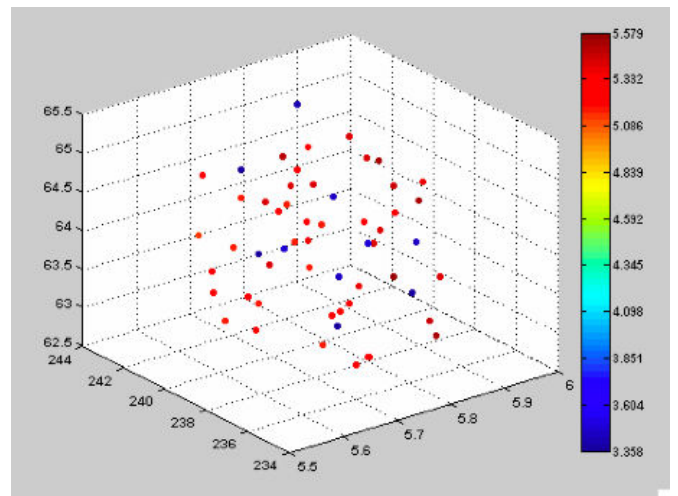**Figure 6. Concentration as a function of input factors**
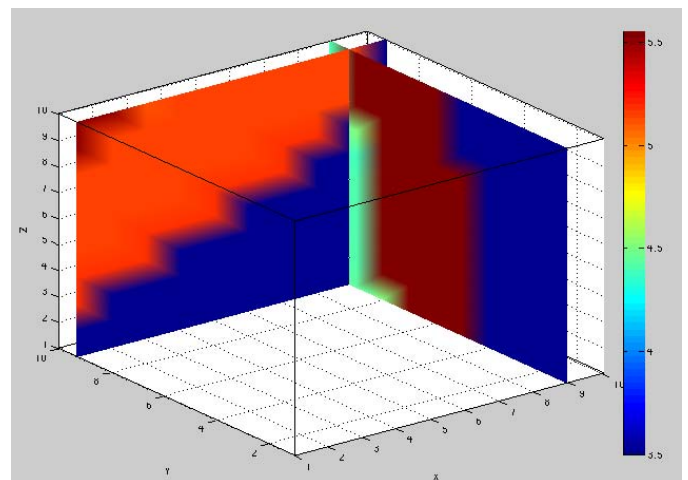

Figure 7. Profit as a function of input factors

Figure 8. Variation of profit (slice)

IV. DISCUSSION

A. Experimental Design

The simulation tool that models the ethanol process does not seem to imitate a physical process because of its non-linear nature. Speaking with the operators in a real setting would give us a much better idea of what the operating ranges would be, what the initial pilot points would be, and how to go about setting up the experiments.

Alternatively, the simulation tool allowed us to run experiments very easily. If we were running these in actuality, we would have had to have been much more calculated in our exploration of the factors and their effects.

In this project we had two objectives. Essentially we wanted to maximize profit. Because profit was varied so dramatically with concentration, we found that it was easier to maximize concentration first. Then, we made adjustments to fine-tune the concentration around the maximum profit.

V. CONCLUSIONS

We conducted an experimental study to optimize the yield (concentration and profit) from an ethanol distillation process. While profit maximization was the primary objective, we chose to start by optimizing concentration, and then maximized profit once an operating point that yielded a high concentration was achieved. This approach was chosen because profit is a function of the concentration, and is also severely impacted by process failure due to repair costs.

We took an approach of first finding an operating range for the input parameters, and then conducting a factorial experimental design and a response surface analysis to arrive at an optimal operating point. As a result of our study, we were able to determine a robust operating point that yielded a high concentration (of 96%) and a high profit level (of $5441).

Our study illustrated the importance of understanding the underlying process in selecting a suitable experimental design and a good pilot operating point.

VI. LESSONS LEARNED

A. Understand your process

A solid understanding of the process is very important to running a successful experiment. This understanding helps with everything, from setting correct experimental levels to interpreting data correctly. To learn about the process it is important to either speak with operators or learn about the technology and theory. Understanding to model was difficult in this case, and would have been much easier if we had been able to ask questions.

B. A good starting point helps

It is difficult to set experimental levels accurately. Working from a starting point that is arbitrary can lead to answers that are local rather than global optimums.

C. Plan ahead

This simulation made it easy to run as many experiments as we needed to come to a conclusion. In practice, we would be constrained by time and money. Really thinking about the question that is trying to be answered and developing a clear set of steps to get there is very helpful in keeping the number of experiments, time and cost to a minimum, while still finding all the critical points of the process.

REFERENCES

[1] Geoff Vining and Scott Kowalski, Statistical Methods for Engineers, Second Edition, pp.567.
[2] Geoff Vining's Home Page, http://kitchen.stat.vt.edu/~vining/
[3] Source code for the simulator, http://kitchen.stat.vt.edu/~vining/distill.html
[4] Sample project description, http://kitchen.stat.vt.edu/~vining/distill-des/