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Energy production, distribution, and pollution controls: Combining engineering and economic analysis to enhance efficiency and policy design

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ENERGY PRODUCTION, DISTRIBUTION, AND POLLUTION CONTROLS: COMBINING ENGINEERING AND ECONOMIC ANALYSIS TO ENHANCE EFFICIENCY AND POLICY DESIGN

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of

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David F. Perkis

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This is dedicated to my wife, Kristin, and my children, Andrew and Olivia. Your commitment to my work, patience in my absence, and love in my presence have meant more to me than you will ever know.

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ABSTRACT

Perkis, David F. Ph.D., Purdue University, December 2014. Energy Production, Distribution, and Pollution Controls: Combining Engineering and Economic Analysis to Enhance Efficiency and Policy Design. Major Professor: Wallace Tyner.

Three published articles are presented which focus on enhancing various aspects of the energy supply chain. While each paper adopts a different methodology, all three combine engineering data and/or techniques with economic analysis to improve efficiency or policy design within energy markets.

The first paper combines a chemical engineering plant design model with an economic assessment of product enhancements within an ethanol production facility. While a new chemical process is shown to achieve greater ethanol yields, the animal feed by-products are denatured and decrease in value due to the degradation of a key nutritional amino acid. Overall, yield increases outweigh any costs, providing additional value to firms adopting this process. The second paper uses a mixed integer linear model to assess the optimal location of cellulosic ethanol production facilities within the state of Indiana. Desired locations with low costs are linked to regions with high yield corn growth, as these areas provide an abundance of corn stover, a by-product of corn and a cellulosic source of ethanol. The third paper implements experimental economic methods to assess the effectiveness of policies intended to control prices in emissions permit markets. When utilizing reserve permit auctions as an alternative to setting explicit maximum prices, prices are elevated beyond the theoretical predictions of the model within the conditions of the experiment. The most likely cause of higher prices is the negotiating power provided to sellers by grandfathering permits as evidenced by higher than expected welfare gains to sellers.

Before presenting the articles, a discussion is introduced regarding the role of assumptions used by economists. For each article, a key assumption is highlighted and the consequences of making a different assumption are provided. Whether the consequences are large or small, the benefits of elucidating our models with assumptions based on real world behaviors are clearly demonstrated.

CHAPTER 1. INTRODUCTION

Scientific theories are distinguished from myths merely in being criticizable, and in being open to modifications in the light of criticism. They can be neither verified nor probabilified.

Karl Popper, Realism and the Aim of Science (Karl Popper, 1992)

Since the financial crisis of 2008, economists have been looking for answers as to what went wrong with the banking system and the economy. While theories abound, Nobel laureate Paul Krugman provides some wise insight when stating that "the economics profession went astray because economists, as a group, mistook beauty, clad in impressive-looking mathematics, for truth." (Paul Krugman, 2009) Often hidden in many of our mathematical equations are simplifying assumptions. If these assumptions are incorrect but on the periphery of the problem at hand, then it is often not an issue. If, however, there are incorrect simplifying assumptions which change some key aspects of an economic problem, and other conclusions are built on top of these assumptions, then many of these conclusions are likely to be erroneous.

The fields of energy and environmental economics lend themselves to combining engineering and economic analysis to identify solutions to technological hurdles and policy debates. Beyond simply lending technical data to the economist, research methods in the engineering sciences can prove useful. While no one would expect any researcher to provide a model that avoids the criticisms of an empiricist of the ilk of Karl Popper, practiced engineers are often quite skilled at adopting simplifying assumptions while maintaining a few essential necessary complexities which allow the model to represent real world behavior.

The three enclosed chapters each focus on a distinct issue related to optimizing energy supplies in the United States through improvements in either productive efficiency or policy design[1]. Each chapter also depends on engineering and scientific data to either describe or solve an economic problem. Finally, each chapter provides an example of how a simplifying assumption could cause a researcher to go astray, whereas an assumption based in real world behavior provides more reasonable results.

1.1 There are Few Representative Molecules

The first paper offers an economic assessment of a manufacturing process intended to generate larger yields of ethanol and more value from corn (David Perkis et al., 2008). The intent of the process is to transform distiller's dry grains (DDGS), a by-product of ethanol production used as a source of nutrition for hogs and cattle, into a higher value feed by increasing protein concentrations. This would be achieved while simultaneously extracting more pure ethanol from the DDGS. In this way, value would be added to two product streams with the only added costs being those related to additional capital and processing expenditures.

A combined chemical, engineering, and economic cost model demonstrates that the value added from larger ethanol yields outweighs the added manufacturing costs. However, when analyzing the new DDGS by-product via a nutritional assessment, it is determined that in spite of larger protein concentrations, the value has been decreased. The drop in value is caused by the disproportionate degradation of lysine, a key amino acid in the nutritional profile of swine and hogs, due to the use of heat in the new chemical process. In net, the new process still provides added value to large scale production facilities, and subsequent energy supply streams, as the benefits of larger

[1] Each chapter represents a copy of a peer-reviewed article already published in a journal or a set of conference proceedings. Copyright approval has been obtained from each periodical. Citations are provided in each section of this introduction, and any changes to the articles are restricted to formatting for the purposes of this dissertation.

ethanol yields outweigh both the manufacturing and denatured DDGS costs. However, with the expectation that the DDGS would have been enhanced, the returns on investment are not as lucrative as expected.

There is one additional learning from this research to which economists working with engineers and physical scientists would be well served to heed: There are few representative molecules. As economists, we often assume a representative agent, and can often do so while generating very robust and rich results with our models. The physical sciences are much less forgiving of such generalizations. As we see in this paper, measuring the overall concentration of a general classification of molecules (proteins and amino acids) yields different results than examining each molecule's nutritional contribution separately.

Subsequent to publishing, the combined engineering and economic model was further modified for research in biofuel production technology assessment (Rakesh Agrawal et al., 2008, Rakesh Agrawal et al., 2009) and policy design (Wallace E. Tyner et al., 2010a, Wallace E. Tyner et al., 2010b). With regards to the latter, a stochastic component was added to the model in order to assess a variable biofuel subsidy design in comparison to the existing fixed subsidies in the market. It was determined that a properly designed variable subsidy could enhance production value and decrease firm risk while simultaneously lowering the cost of the subsidy to tax-payers.

1.2 The Social Planner vs. Profit Maximizing Firms

The second paper implements a cost minimization model in order to determine the optimal locations for ethanol production facilities from cellulosic sources in Indiana (David F. Perkis et al., 2008). The sources considered are corn stover, a secondary residue from corn crops, and switchgrass, a primary crop requiring dedicated land. Costs which are minimized include those covering the production and shipping of biofuel crops up to the door of the conversion plant.

Two very strong assumptions are adopted for the model. First, production facilities are assumed to be capable of receiving either type of biomass. This would require all facilities to have equipment which converts each type of biomass into a form that can be chemically processed and fermented, and for the cost differential between conversion processes to be negligible. Second, costs are minimized over the network of plants consistent with a social planner's framework. This requires decisions regarding the location of manufacturing sites to be made simultaneously for all facilities in the network.

Perkis et al. (2008) conclude the following regarding the optimal location of manufacturing sites: (1) The probability of having a county with a site is somewhat higher in the top half of the state where the highest yields of corn are produced, (2) Plants in the northwestern section of Indiana use the highest percentage of corn stover and obtain raw materials at the lowest cost, and (3) Plants operating in the southwestern section of Indiana use the largest percentage of switchgrass and operate at the highest cost. These conclusions were consistent over various plant sizes and corn stover removal rate assumptions.

These conclusions are also consistent with what one observes within the industry today. As some of the first cellulosic biorefineries begin production this year, they tend to locate within corn-rich regions, utilizing corn stover pulled from nearby farmland (Tom Doran, 2014). However, industrial practices are not entirely consistent with one of the paper's key assumptions, namely that most sites would process multiple sources of cellulosic material. As manufacturing operations that utilize corn stover come online, they tend to focus solely on this one raw material as their source of biofuel production.

Subsequent to publishing, the model was altered to more closely reflect the assumptions of profit maximization (Appendix A). Instead of minimizing costs over the entire network of locations simultaneously, sites would minimize costs on a rolling basis. For instance, the first site would minimize costs with access to the entire resource base of cellulosic materials. The second site would minimize costs without the raw materials utilized by the first site, and so on. When changing assumptions from that of a social planner to profit-maximizing firms, most sites utilize only one type of cellulosic material, with those first to market focusing on corn stover and those last to market focusing on switchgrass. The main conclusions regarding plant location and cost ordering remain the same.

While the assumption of the social planner did not impact the main results of this paper, it certainly did impact the mixture of cellulosic materials being used by each site. For studies where the proportions of biofuel sources are important, the social planner assumption would lead to erroneous results. Therefore, in subsequent studies conducted by colleagues who wished to use this model, the assumption of profit maximization was adopted (Justin L. Quear, 2008).

1.3 Mathematical Predictions and Human Behavior

The third paper utilizes experimental economic methods to examine the effectiveness of price controls utilized in markets which sell permits allowing firms to emit greenhouse gases and other pollutants (David F. Perkis et al., 2014). Two types of policies are compared in this analysis. The first type, referred to as a hard ceiling, places a legal maximum on permit prices. The second type, referred to as a soft ceiling, releases an additional reserve of permits into the market near the end of the regulated time period. A hard ceiling provides absolute price control while the soft ceiling does not.

To further complicate issues, the mathematics of the soft ceiling requires firm managers to use some foresight while trading by predicting market conditions and optimal behavior when reserve permits are eventually released. If firm managers are skillful in adopting foresight, their behavior should converge towards the theoretical predictions of the soft ceiling model. The set of experiments presented were designed to determine whether subjects trading in experimental markets regulated by a soft ceiling would converge towards the price limit predictions of the model. If they do not, then such policies should likely be redesigned and/or reconsidered before being passed into law.

The paper demonstrates that under certain conditions, the soft ceiling design does not control prices as intended. In some cases, prices are higher than the desired maximum even after subjects have been exposed to the same experimental market structure over 12 repeated periods. One of the most likely culprits is the grandfathering of permits which provides sellers with appreciable negotiating power. This is demonstrated by large shifts in welfare from buyers to sellers in comparison to theoretical predictions.

Regardless of the reason for the model's divergence from theory, this research highlights another issue prevalent within economics: some theories and policies that are mathematically sound may not hold when subjected to the reality of human behavior.

In the natural sciences, experiments are easier to conduct. Engineers and scientists are able to run controlled experiments with physical materials, keeping certain factors constant and varying others. Economists have a more difficult task, as conducting experiments requires working with human subjects as well as anticipating the factors over which the economist has no control. Fortunately, with the growing number of experimental labs within economics departments, more and more researchers are able to test their ideas on a small scale (akin to an engineer's pilot plant) before they are implemented as policy. In doing so, economists can modify their mathematical models to account for human behavior and improve policy design before it is implemented on a larger scale and passed into law.

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CHAPTER 2. ECONOMIC ANALYSIS OF A MODIFIED DRY GRIND ETHANOL PROCESS WITH RECYCLE OF PRETREATED AND ENZYMATICALLY HYDROLYZED DISTILLERS' GRAINS

2.1 Abstract

A modification of the conventional dry grind process for producing ethanol from yellow dent corn is considered with respect to its economic value. Process modifications include recycling distiller's grains, after being pretreated and hydrolyzed, with the ground corn and water to go through fermentation again and increase ethanol yields from the corn starch. A dry grind financial model, which has been validated against other financial models in the industry, is utilized to determine the financial impact of the process changes. The hypothesis was that the enhanced process would yield higher revenues through additional ethanol sales, and higher valued dried distiller's grains (DDGS), due to its higher protein content, to mitigate the drop in DDGS yields. However, there may be no value added to the enhanced dried distiller's grains (eDDGS), even in light of its higher protein levels, as current pricing is expected to be more sensitive to the amino acid profile than the total protein level, and the eDDGS has lower lysine levels, a key amino acid. Thus, there is a decrease in revenue from eDDGS due to the combination of no price change and loss of DDGS yield to ethanol. A 32% increase in net present value (NPV) for the overall operation is expected when applying the process modifications to a 100 million gallon ethanol plant. The financial improvements are a result of the increased revenue from higher ethanol yields outpacing the sum of all added costs, which include higher capital costs, larger loan payments, increased operating costs, and decreased revenues from dried distiller's grains.

2.2 Introduction

The dry grind process converts the entire corn kernel into two main products of economic value, ethanol and dried distiller's grains (DDGS). While ethanol has typically been known as a key component in alcoholic beverages, its rapidly growing use as an automotive fuel, through subsidies and high oil prices, makes it a product of high value. The DDGS co-product is sold as animal feed for swine, cattle, and chickens due to its protein, amino acid, and energy content. However, DDGS also contains some unconverted starch and sugar precursors to ethanol, which, if processed, could increase the ethanol yield of a dry grind facility. Increasing ethanol yields would increase the revenue from ethanol of the dry grind process, and could also enhance the value of the DDGS by creating a product with higher concentrations of protein for animal feed.

A process has been proposed which takes the distiller's grains from the conventional dry grind process and recycles them for further processing and fermentation, resulting in higher yields of ethanol and an enhanced dried distiller's grains (eDDGS) product with increased protein levels (Kim et al., 2007). The conventional process (Figure 2.1), or "base" process, grinds the corn and breaks it down into simple sugars to be fermented into ethanol. The ethanol is then separated by distillation off the top of a column, while the bottom products are further processed to separate water from the distiller's grains. The proposed modifications (Figure 2.2) would subject the material from the bottom of the distillation column to further processing, including a pretreatment heating step and subsequent hydrolysis of polymeric sugars and residual starches by enzymes, and then separate the sugar-rich "pretreated" liquid to be recycled back through the original hydrolysis and fermentation processes in order to increase ethanol yields. The remaining distiller's grains not recycled with the pretreated liquid would be dried and sold as eDDGS, an animal feed with higher protein levels than conventional DDGS.

A dry milling model, called the DM model based on dry milling of corn (Dale and Tyner, 2006a), was developed using MS Excel (Microsoft Corporation, 2003) to monitor the financial feasibility of the conventional dry grind process given market trends for the costs of corn, the price of ethanol, and other product and input prices. Validation of this model included comparisons of capital costs and variable costs against industrial estimates from the Ethanol Production Handbook (BBI Int., 2003) and a 2002 Cost of Production Survey (Shapouri and Gallagher, 2005) respectively. In the 100 million gallon nameplate range, the DM model calculated capital and variable costs valued at 97% and 103% of their respective industrial estimates (Dale and Tyner, 2006a). Calculations performed at other nameplate ranges were similarly close. Thus, there is confidence that the DM model can be utilized to determine the financial feasibility of the conventional dry grind process, and can be augmented with a technology module and adjusted pricing to analyze the financial costs and benefits of the dry grind process with pretreated liquid.

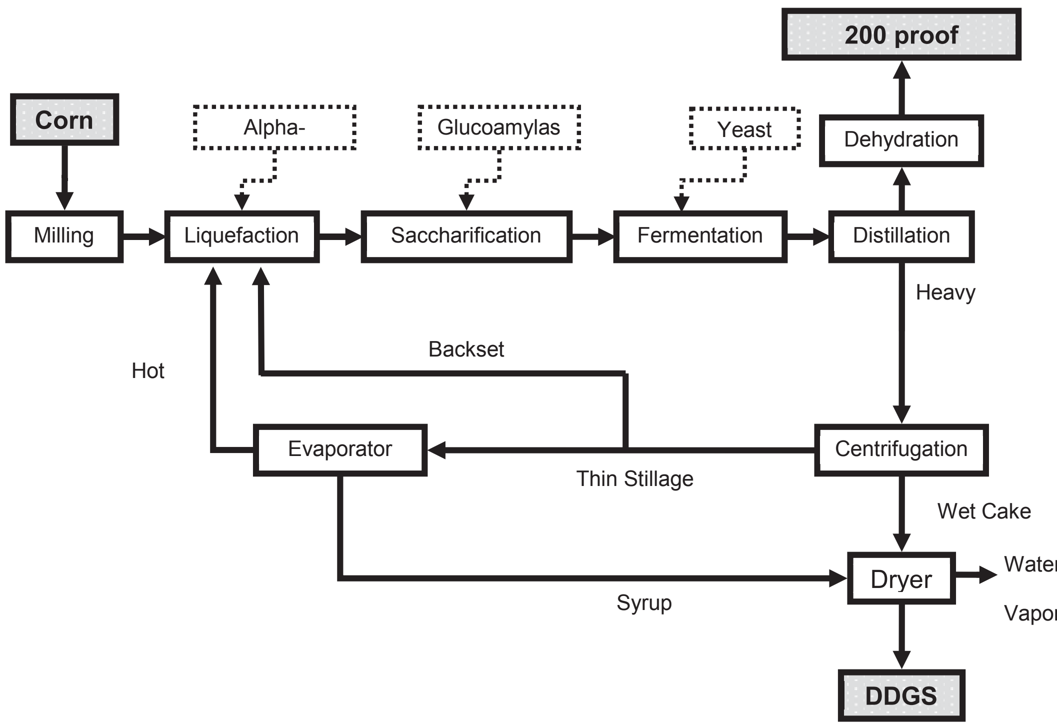

Figure 2.1 Schematic Flow Diagram of Current Dry Grind Ethanol Process. Water Utilization for Cooling of Heat Exchangers Is Not Shown (Kim).

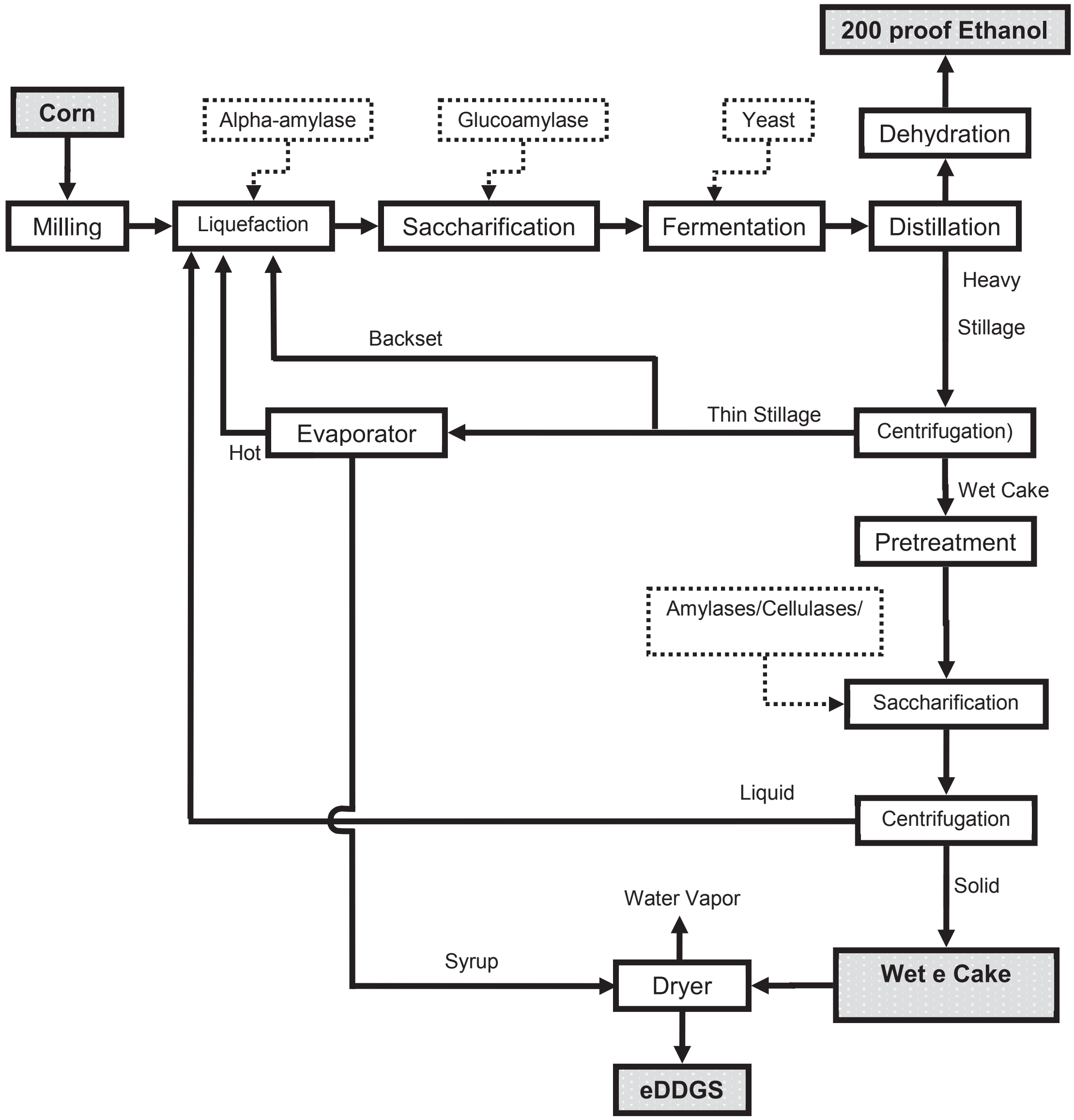

Figure 2.2 Schematic Flow Diagram of Alternative Dry Grind Process with Recycle of Distiller's Grains (Wet Cake) to Liquefaction (Kim).

2.3 Methodology

The DM model is based on the process in Figure 2.1, which takes yellow dent corn, hydrates the ground corn particles, breaks down the starch into simple sugars using enzymes, and then ferments the simple sugars into ethanol. The ethanol is then separated from the remaining distiller's grains, which are also processed in order to sell to the animal feed market. The DM model takes specific flow rates (ethanol output, water recycle), conversion rates (hydrolysis and fermentation yields), and product and input characteristics (grain, ethanol, DDGS) to determine all other flows in the process (Dale and Tyner, 2006b). Especially important are the product and process stream moistures, as these determine how water is managed in the process, both in terms of drying capacity and recycle use. With this information, all product flow rates and densities can be estimated, allowing for equipment sizing, motor loads, and temperature and thermal energy requirements.

Market prices for variable costs (grain, chemicals, energy, and utilities) and revenues (ethanol, DDGS, CO2) are incorporated into the model to determine yearly operating costs and benefits in real terms. The equipment sizing and specifications allow for pricing of individual units to be determined. Equipment prices are scaled to the current year by the Marshall Swift Index (chemical engineering, 2007). For large nameplates such as this, the DM model uses the Fixed Capital Investment (FCI) method to determine the Total Capital Costs (TCC) based on equipment costs (Dale and Tyner, 2006a). Working capital based on initial real operating expenses is added in, and the resulting Total Capital Investment (TCI) is obtained. Part of this investment, as well as any capitalized interest, is assumed to be financed through loans. Finally, interest and discount rates are utilized to determine both nominal and real loan payments and perform the final benefit-cost analysis to determine the financial measures of interest such as net present value (NPV) and the internal rate of return (IRR).

2.3.1 The Base Process

The material balance for the conventional dry grind process (Kim, 2007) was normalized by setting the ethanol output volume equal to the hourly flow rates assumed in the DM Model, and subsequently adjusting the starch and sugar conversion yields in order to match the corn input rates of the material balance. Additionally, adjustments to process flow moisture levels and backset recycle rates were made in the DM model to match the material balance as closely as possible.

Once all the material and energy flows were determined based on this normalization, prices were updated to represent current market values (Table 2.2). Commodity prices were updated based on market pricing in the last week of May 2007. Specialty chemical prices which typically show less volatility were updated using information from industry obtained during the first half of 2007. As previously stated, capital costs for equipment are automatically updated in the DM model with the Marshall & Swift Equipment Cost Index, a commonly used engineering equipment inflation index. In some cases, information from industry differed in that some equipment costs had increased more dramatically than estimated by the Marshall & Swift Index, likely driven by the increased demands on equipment by the ethanol industry. In such situations, the equipment cost was inflated to more accurately represent prevailing market prices. The DDGS price was also updated based on regional market prices, as opposed to being estimated based on its historical relationship to corn or soy bean meal prices.

Once the base process model and all pricing was updated, loan terms were determined and project financials were calculated.

2.3.2 Pretreated Liquid

A technology module containing the parameters of the pretreated liquid process has been added to the base DM model in order to assess the financial impact of building a plant with the pretreatment process. The module, as with the material balance, assumes an equal rate of input corn, adjusting the remainder of the process flows with scaling factors as indicated by the material balance (Kim et al., 2007). For instance, while the pretreated liquid brings in more sugars to the fermentation process, increasing the requirements of yeast, it is assumed that no additional starches are introduced into the liquefaction step with the pretreated liquid. Thus, the enzymes used in the base process can be maintained at the same levels since they are tied to the starch flow rates coming from the corn. Some rates increase such as the ethanol processing streams since higher yields are obtained than in the base process. Finally, some of the rates decrease such as the DDGS processing streams as more of the fermentable starches and sugars are recycled. For water and thermal energy rates, it was assumed that these would be consumed by the process at the same rate for each gallon of ethanol as the base process. This is believed to be a conservative estimate as more savings would likely be realized in the pretreatment process by recycling water and using effective heat exchange.

Existing equipment has been resized and new items are assumed to have been purchased, including a saccharifaction tank for the enzymatic hydrolysis of the cellulose and residual starch in the combined wet cake/thin stillage, and a centrifuge to separate out the resulting pretreated liquid from the remaining distiller's grains. Resizing is performed based on the key operating parameters used for each piece of equipment. This parameter is often as simple as the throughput, although some capital is sized based on other factors, such as residence time or drying loads.

With flows rates and equipment sizing determined, market prices can be applied to the pretreated liquid technology module just as in the base process. Loan terms are then calculated and the financials for the pretreatment module are determined, such as annual net benefits, NPV, and IRR.

2.3.3 Price Expectations for eDDGS and enzymes

While most market prices apply to both the base and pretreated liquid processes, there are two additional components in the new process without a market price, the added enzyme mixture and eDDGS. Prices for the new enzyme mixture are estimated by the supplier (Genencor International, Inc.) and are based on the additional ethanol yields (in gallons) obtained in the new process.

It was expected that the higher protein levels in eDDGS would bring higher prices, without having to pay a premium for the enzyme requirements of the pretreated liquid stream. The eDDGS price is estimated based on the change in value compared to DDGS as determined by a swine feed ration pricing model. The compositional analyses of DDGS and eDDGS (Table 2.1) required for the pricing model were performed by the Experiment Station Chemical Laboratories, University of Missouri-Columbia, following methods outlined in a previous paper in this series (Kim et al., 2007).

Table 2.1 Total Swine Feed Nutrition Limits in Feed Cost Model for Swine Feed Containing 15% DDGS or eDDGS.

	MINIMUM	MAXIMUM
Crude Protein	0.160	
App. Dig. Methionine+Cystine	0.502	
App. Dig. Threonine	0.518	
App. Dig. Tryptophan	0.144	
Calcium	0.720	0.820
Available Phosphorous	0.240	
Crude Fat		8.00
App. Dig. Lysine	0.850	
Isoleucine	0.468	
Valine	0.570	
Vitamin Premix	0.150	0.150

A swine feed pricing model was chosen due to the strong dependence of swine health on the amino acid and nutrient profile of swine feed (National Research Council, 1998). It is desirable that eDDGS would increase in value in all markets where it is purchased, whether for cattle, swine, or any other animal which currently consumes DDGS. Since initial analytical results showed a substantial increase in protein for the eDDGS, it was expected that this protein would yield higher value for eDDGS. As swine do have a more particular diet based on specific amino acid levels (Thaler, 2002), it is believed that value determinations based on the added constraints of a swine diet will represent a true lower limit for eDDGS pricing in the market.

For the swine feed model, DDGS or eDDGS was assumed to be mixed into the animal feed at a 15% level for grower swine. Because previous studies have shown that dried distiller's grains with fat content similar to that of standard DDGS can cause reduced belly firmness and more soft fat when added at levels above 20% of a grower swine's diet, current recommendations entail starting the swine at 10% DDGS and increasing the feed diet up to a maximum of 20% (Thaler, 2002). The midpoint of 15% was therefore chosen for this analysis. However, several percentages were tested in the model between 10% and 20% in an attempt to confirm the robustness of pricing estimates.

The swine feed model sets limits on amino acids (see Table 2.1), as well as total protein and other minerals (National Research Council, 1998 and Hill et al., 1998). Prices and nutrient levels are included for all other feed ingredients. The total feed cost is minimized by adjusting corn, soy bean meal, vitamins, and amino acid supplements to obtain the desired nutrient requirements at the lowest price possible, and a shadow value is calculated for the DDGS. In this analysis, shadow values for DDGS and eDDGS were obtained, and the ratio of the two shadow values was applied to the DDGS market price in order to estimate an expected market price for eDDGS.

2.4 Results

Based on a dry grind nameplate level of 100 million gallons of ethanol, a corn price of \$3.82 per bushel, and a denatured ethanol price of \$2.23 per gallon (Table 2.2), the DM model predicts an NPV of \$162 million (Table 2.3) over the 25 year life of the project, with operations beginning in year 3. This includes a \$33.5 million yearly net operating benefit (Table 2.4), not including initial annual loan payments of \$11 million

(Table 2.3). The loan pays off 60% of the total capital investment of $148 million plus any capitalized interest. The total capital investment per gallon of ethanol is $1.48. While this number may seem somewhat low, some of the large capital investment values found in industry may be due to a bubble from the growing ethanol demand. It is likely that TCI values will soon return to lower levels more in line with our model. More annual cost and revenue data can be found in Table 2.4.

Table 2.2 Key Prices and Economic Assumptions
(Price Data Taken from Chicago Board of Trade, Ethanol Producers Magazine, Bloomberg.com, and other Industrial Contacts)

	Value
Corn price	$3.82 / bu.
Soybean meal price	$217 / ton
Ethanol price	$2.23 / gal.
Gasoline price	$2.27 / gal.
DDGS price	$105 / ton
CO2 price	$6.36 / ton
Alpha-amylase	$5.50 / lb.
Gluco-amylase	$3.15 / lb.
Debt interest rate	8.7%
Debt/Equity ratio	60/40

Table 2.3 Capital and Financial Analysis of the Base and Alternative Processes. All Values in Real Dollars

	Base Process	With Pretreatment
Total Capital Investment	$148,260,425	$158,454,889
40% Equity Paid	$59,304,170	$63,381,955
Initial Loan Payment	$10,901,732	$11,651,340
IRR (real)	33.1%	38.5%
NPV	$161,957,921	$214,581,147
Change in NPV		$52,623,226
% diff from base		32%

Table 2.4 Annual Revenue and Operating Cost Details of the Base and Alternative Processes

Revenues	Base Process	With Pretreatment
Ethanol	$223,000,000	$251,254,754
DDGS or eDDGS	$37,694,685	$28,735,669
CO2	$2,004,506	$2,271,200
Total Revenue	**$262,699,191**	**$282,261,623**

Costs	Base Process	With Pretreatment
Materials	**$166,843,443**	**$171,035,283**
Grain	$136,176,590	$136,176,590
Enzymes	$13,532,318	$16,066,376
yeast	$1,018,105	$1,056,774
SO2	$4,766,430	$4,947,464
denaturant	$11,350,000	$12,788,078
Energy and Water	**$33,707,243**	**$39,552,795**
Thermal	$25,576,643	$29,602,759
Electrical	$7,673,417	$9,434,927
H2O	$457,184	$515,110
Indirect	**$27,917,734**	**$30,813,358**
Labor	$6,553,650	$7,017,489
Taxes	$8,234,656	$9,698,408
Liscence Fees	$5,253,984	$5,645,232
Maintenance	$5,253,984	$5,645,232
Misc.	$2,621,460	$2,806,996
Total Operating Costs	**$229,165,569**	**$241,401,436**

Net Benefits	Base Process	With Pretreatment
without loan	**$33,533,622**	**$40,860,187**

2.4.1 Pretreatment Module: Pricing Adjustments

The new enzyme mix cost is estimated to add $0.20 per additional gallon of ethanol above 100 million gallons. With 12.7 million gallons of additional ethanol being produced by the pretreatment process (Table 2.5), there are roughly $2.5 million in additional enzyme costs.

Table 2.5 Input and Output Rate Changes of Major Ingredients between the Alternative Process and the Base Process

	Base Process	With Pretreatment
Yellow Dent Corn (tons)	998,143	998,143
Ethanol (gal)	100,000,000	112,670,293
DDGS (tons)	358,997	277,951

eDDGS drops in value roughly 1.5% compared to the base DDGS currently in the market as determined by the swine feed model. This drop is due to the loss of lysine in the eDDGS samples. Our base DDGS has 0.87% digestible lysine while the eDDGS has 0.54% (Table 2.6). Lysine is a key ingredient in swine feed (Thaler, 2002), and such a drop forces the model to supplement the feed with higher cost, lysine rich components and supplements, resulting in a very slight drop in value of the eDDGS. If the lysine to protein ratio were to stay the same, we would predict an eDDGS lysine level of 1.27% and an increase in eDDGS value of 6.7% vs. the base DDGS.

2.4.2 Pretreatment Module: Process Flows, Capital, and Operating Costs and Revenue

The ethanol yield increases with the pretreatment module by 12.7% (Table 2.5). This has a substantial impact on plant revenue, increasing revenue by over $28 million annually due to ethanol yields alone. A couple of other notable changes are driven by this yield increase. All ethanol processing equipment is more expensive due to the increased throughputs, and the utilities are more expensive as well, as energy and water increase in cost from $33.7 million to $39.6 million (Table 2.4).

Table 2.6 DDGS and eDDGS Nutrient Analysis

	DDGS	eDDGS
Crude Protein	28.3 %	41.2 %
App. Dig. Methionine+Cystine	1.08 %	1.14 %
App. Dig. Threonine	1.08 %	1.33 %
App. Dig. Tryptophan	0.19 %	0.21 %
Calcium	0.031 %	0.035 %
Phosphorus	1.07 %	1.20 %
Available Phosphorous	0.92 %	1.02 %
Crude Fat	14.5 %	14.7 %
App. Dig. Lysine	0.97 %	0.58 %
Crude Fiber	6.52 %	2.88 %
Isoleucine	1.13 %	1.53 %
Valine	1.48 %	1.94 %

While the ethanol yields drive up the throughput and prices of certain pieces of equipment, other capital expenditures are unaffected, or even decrease, due to the new process flows. For instance, the hammer mill cost would be identical due to the constant corn input rates (Table 2.5). Similarly, the costs of liquefaction and saccharification tanks would increase minimally as the pretreated liquid stream does not increase throughput in these two tanks substantially. In the case of eDDGS drying and processing, the lower yields actually lessen the capacity requirements of the drum dryers, resulting in a decrease in capital costs through this part of the process. The net result is that the pretreatment process module increases the equipment costs for existing equipment by just over $750 thousand, with another $1.4 million needed for the new equipment in the process (Table 2.7). These two increases lead to a total capital investment (TCI) of $158.5 million, or a 6.9% increase in TCI compared to the base process. With the ethanol yield increasing by 12.7%, an efficiency in TCI per gallon of ethanol is realized as this value decreases from $1.48 in the base process to $1.41 in the pretreated liquid process.

Table 2.7 Capital Costs for the Base Process and Alternative Process

	Base Process	With Pretreatment
Total Existing Purchased Equipment	$30,015,719	$30,782,203
New Purchased Equipment		$1,357,896
Other Capital Costs and Working Capital	$118,244,707	$126,314,789
Total Capital Investment	$148,260,425	$158,454,889
Total Capital Investment / Gallon Ethanol	$1.48	$1.41

Finally, the decrease in eDDGS yields, with no appreciation in its value, results in a revenue loss of nearly $9 million annually (Table 2.4), diminishing some of the revenue gains from the ethanol.

2.4.3 Pretreatment Module: Financials

The loan payments increase for the pretreated liquid process, due both to increases in capital requirements, as well as increases in working capital (based on operating costs tied to higher values for capital and ethanol revenue). However, with the lower capital cost per gallon of ethanol, and the large increase in ethanol revenue, it is not surprising that the NPV for an operation which includes the pretreatment and enzymatic hydrolysis technology is $214.6 million, or a $52.6 million increase compared to the base process (Table 2.3). The IRR also increases to 38.5%, compared to 33.1% for the base process.

2.4.4 Sensitivity to eDDGS Pricing

If any variability exists with respect to lysine losses in the distiller's grains due to the pretreatment technology, it would be useful to understand the impact on the plant financials. Assuming no loss of lysine in the protein, and an eDDGS lysine level of 1.27%, the adjusted value of eDDGS (a 6.7% increase instead of a 1.5% decrease) yields an NPV of $230.7 million, or $16 million higher than the estimate with the lower eDDGS value.

2.4.5 Sensitivity to Enzyme Mix Pricing

The enzyme mixture which hydrolyzes the pretreated distiller's grains by far represents the most significant raw material cost increase, and brings an additional $2.5 million in material costs to the operation. Without this added cost, the net operation benefits of implementing the pretreatment and hydrolysis of distiller's grains is $9.9 million. Thus, added enzyme costs cut into this net benefit by 26%. Looking at the sensitivity of pricing for the enzyme mixture, a decrease in the new enzyme mixture cost by 20% would yield a net yearly benefit of $7.8 million and an NPV of $218.2 million compared to $7.3 million and $214.6 million respectively for the assumed pricing. However, if the enzyme mixture cost ended up being higher by 20%, the net yearly benefit and NPV would drop to $6.9 million and $211.0 million respectively.

2.5 Summary and Conclusions

Based on the conservative practice of utilizing swine feed models to determine the value of dried distiller's grains, the eDDGS product does not show an increase in value as anticipated compared to the base DDGS due to the loss of lysine through the pretreatment and enzymatic hydrolysis processes, lysine being a particularly important amino acid in the swine diet. While using a swine diet might seem restrictive as other animals may benefit more from the high protein content in eDDGS, it is not known whether such a product differentiation is possible in the DDGS market, being able to sell the product for one type of animal feed at a premium while eliminating other markets. Thus, the restrictions of a swine diet may be appropriate. If this is the case, then finding ways of retaining lysine could prove important. While the value of eDDGS did not decrease substantially compared to the base, further losses of lysine could drop the value enough that overall feed costs become prohibitive to the farmer, and eDDGS loses more of its worth to the swine population.

Nevertheless, even with the eDDGS value not appreciating, the pretreatment technology does add value to a conventional dry grind operation at current corn and ethanol prices. The large yield increases in ethanol, combined with its value over that yield, increases revenues substantially, more than making up for added capital costs, higher operating costs, and revenue losses from decreased DDGS yields. Thus, at current ethanol prices, the economics of the pretreatment technology are encouraging, and finding a way to maintain lysine levels in the dried distiller's grains would likely make the technology even more economically attractive. Furthermore, any reductions in pricing of the enzyme mixture are shown to add to the economic gains of the pretreatment and hydrolysis process. It is also known that lower ethanol prices would reduce the gains of hydrolyzed distiller's grains substantially. For instance, given the assumptions used in this analysis, the breakeven ethanol price for the pretreatment process is roughly \$1.95 per gallon compared to \$1.99 per gallon for the conventional dry grind process. Any changes which either increase the value of the eDDGS or decrease the cost of the enzyme mixture would help to lower this breakeven price even more, thus making ethanol production by the dry grind process feasible over a larger range of ethanol prices.

2.6 Acknowledgments

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CHAPTER 3. SPATIAL OPTIMIZATION AND ECONOMIES OF SCALE FOR CELLULOSIC TO ETHANOL FACILITIES IN INDIANA

3.1 Abstract

Based on cellulosic biomass yield projections of a recent national study, the optimal spatial distribution and size of cellulose to ethanol conversion facilities is determined for cellulose sources in Indiana to be converted to ethanol through a biochemical conversion process. Such sources include corn stover and switchgrass. A cost minimization approach is implemented that optimizes over the raw material and transportation costs of the process, with economies of scale included for large facilities. Due to the abundance of corn stover and its current low cost as a byproduct of corn production, a high concentration of facilities in the northwest section of Indiana is ideal. Such plants would utilize high levels of corn stover and operate at relatively lower cost than other facilities in the state. Other regions of the state would have fewer facilities, several specializing in switchgrass and operating at a higher cost. Economies of scale similar to those found in corn to ethanol facilities are likely to support large sized plants given current yield projections. However, if more conservative biomass yield projections are expected due to lower collection or land utilization rates, the economies of scale needed to support large plant sizes nearly doubles, increasing the likelihood of an optimal strategy in which smaller facilities are more broadly distributed around the state.

3.2 Introduction

Ethanol output has grown significantly in recent years, both in Indiana and across the United States. With the desire to promote cleaner, renewable fuels, both the federal and state governments have instituted subsidies intended to increase output. In December 2007 Congress passed and the President signed the "Energy Independence and Security Act of 2007" which contains a renewable fuel standard (RFS) requiring 35 billion gallons of ethanol by 2022, of which at least 16 billion must come from cellulosic sources (U.S. Congress, 2007). Additionally, recent increases in gasoline prices compared to the historically low prices experienced in the United States likely will continue to put upward pressure on the demand for substitutes. As less expensive production technologies in ethanol manufacturing come online, ethanol substitution levels in fuel mixtures may continue to increase.

While there is much excitement about this ethanol boom and the potential for profit, there are also undesirable outcomes for participants in closely related markets. Specifically, with corn being the primary input for the ethanol production process, livestock producers dependent on corn as a feed ingredient have been negatively impacted by rising corn prices. Such factors also impact food markets as higher costs for feed are passed on to consumers of chicken, eggs, dairy, beef, and pork through higher prices. Thus, while ethanol shows great potential as a cleaner fuel that could decrease U.S. dependence on foreign oil, there are concerns about how increased ethanol output levels and the induced demand for corn will impact the affordability of certain dietary staples.

Given the potential for adverse price effects in food markets, there is a desire to develop alternative sources of the raw materials needed for ethanol production. Materials rich in cellulose show great potential as ethanol feedstocks. Not only can they be converted to the necessary precursors for ethanol production, but many cellulose sources are natural by-products of other farming and manufacturing processes. Corn stover and wood trimmings are two common examples of by-products of corn farming and logging respectively (Perlack et al., 2005). Furthermore, some high energy sources of cellulose that would be grown as primary crops can be grown on terrains hostile to corn and other crops, thus in some cases being produced on currently uncultivated lands without having to displace food production.

Recently, the “Billion-ton” study investigated the potential for U.S. grown biomass sources to provide enough ethanol to replace 30% of domestic fuel consumption (Perlack et al., 2005). In short, the authors conclude this would be feasible, with cellulose based sources making up a substantial portion of the over 1.3 billion dry tons of biomass resources projected to be available for conversion to fuels.

The State of Indiana has benefited from the push for ethanol and other biomass based fuels. The large quantity of farmland dedicated to growing corn has made Indiana an attractive site for the construction of conventional corn to ethanol dry grind manufacturing facilities. With the push for alternative biomass to produce ethanol, it is useful to begin assessing how Indiana can position itself to take advantage of cellulosic materials if the Billion-ton study projections are correct. The Billion-ton study anticipates that 18.3 million dry tons of cellulose feedstocks would be available in Indiana given proper land utilization. As these sources are developed, and firms begin to construct facilities for conversion to ethanol, there will be many questions affecting the welfare of firms and citizens alike. For instance, where should manufacturing facilities be located and how large should they be? Which locations will best take advantage of the cellulose source materials with respect to minimizing costs? What impact will a potentially large network of facilities have on our roads and highways? What will be the impact of new manufacturing facilities and some newly cultivated land on the Indiana job market and the environment?

The intent of this paper is to begin to answer some of these questions and to provide a framework for follow-up studies. Specifically, it seeks to determine an optimal spatial distribution of ethanol plants within the state of Indiana given the projections of biomass availability projected by the Billion-ton study and detailed cost information for harvesting, storing, and shipping biomass products (Brechbill and Tyner, 2008). Additionally, this paper provides guidance regarding the optimal size of ethanol facilities based on economies of scale. One of the key assumptions is that conversion facilities will use all of the cellulose materials grown within Indiana, and only these materials, in the production of ethanol. This is acknowledged to be a strong assumption, but one which should not dramatically alter the findings of the study. Since crop costs grow with increased shipping distances one would expect that only crops near the borders would be shipped across state lines, and there is no reason to believe that more crops would be shipped in one direction or the other. It is therefore believed that the impact of this assumption on the conclusions should be small.

Projections of optimal plant locations have been made in the past. Notably, Nelson projected plant locations across Indiana for 40 equal output sites (Nelson, 1981). However, Nelson focused on agricultural residues without taking into account cellulose source crops which are specifically grown for conversion to ethanol. Additionally, Nelson made regional assumptions of harvest rates not required here due to the detailed county level data provided by the Billion-ton study. Given expected residue and crop outputs in this data, a specific county level analysis can be performed by combining the yield data with inter-county distances and transportation costs. Additionally, this paper considers some of the larger throughput rates anticipated to benefit from economies of scale based on historical experience from fermentation of corn-based sugars (Dale et al., 2006).

Another series of papers exemplified by English et al. (2000) has a broader scope by investigating the impact of corn stover and other biomass output expectations on the economies of several corn-growing states including Indiana, even including output prices and other factors for sensitivity analyses. However, English et al. focuses on economy wide results at the state level as opposed to county level output decisions, the main focus of this paper's spatial distribution plan. Additionally, this paper utilizes the most recent county yield estimates (Billion-ton study) and biomass cost information (Brechbill and Tyner, 2008) for Indiana.

This paper will focus on the anticipated 14.6 million dry tons per year of corn stover and switchgrass available to be processed by biochemical conversion (Perlack et al., 2005). This process breaks the cellulose down to simple sugars using enzyme hydrolysis, and then ferments the sugars to produce ethanol. Enzymatic hydrolysis and fermentation are currently used to convert corn to ethanol and would be conducive to the cellulose sources considered in this study. These sources are corn stover, an agricultural residue from corn production, and switchgrass, a high energy primary crop (US DOE, 2006). In addition to considering the optimal spatial distribution and size of plants given the projections of the Billion-ton study, an additional scenario will be tested making more conservative assumptions with respect to collection rates of corn stover, as well as land utilization and biomass conversion rates for both corn stover and switchgrass.This is the second page of your chapter.

3.3 Methodology

Focusing on biochemical conversion facilities, it is assumed producers can utilize one of two plant sizes, a large plant (100 million gallons/year) or a small plant (50 million gallons/year), in order to convert Indiana's projected corn stover and switchgrass into ethanol. It is also assumed that this conversion process will be robust enough to handle either of the two feedstocks in varying proportions within one plant. While this might assume an optimistic level of manufacturing robustness, the key components of each material which are hydrolyzed are similar. It seems feasible that enzyme mixtures, as well as technological modifications of the crops themselves, could be developed to provide such robustness. Finally, the following simplifying assumptions are made: (1) each county will have at most one manufacturing facility, (2) the construction and operating costs are identical for each plant except for the biomass raw material costs and an economy of scale factor which will be represented by an added per gallon cost for the smaller plant, and (3) cost differences exist only in the growing (switchgrass), harvesting, and transportation costs of the biomass raw material mixture which is input into the process.

The objective for firms is to maximize their profit, which is revenue less costs. Since plants of modest size are assumed, individual plants should not have an impact on the price of ethanol and unit revenues are thus assumed to be identical for each site regardless of its location. Thus, to maximize profits, firms must focus on minimizing their costs. Since construction and operating costs are assumed to be identical for each site, optimization focuses on the production, harvesting and transportation costs of biomass. Specifically, how do the relative costs for each crop impact the choice of the input mix in order to minimize costs.

This model will assume that costs are minimized over all sites, even though each site may be owned by a different enterprise. While this appears to be more of a central planning solution than one of competitive firms maximizing profits, the general results should be similar, with plants locating based on the comparative advantages relative to surrounding counties (Nelson, 1981). In reality plants will likely contract for cellulose raw materials before the plant is even constructed. The early plants will locate in least cost areas and will contract for available raw material in those areas. Since the purpose of this exercise is to determine the use of all biochemically converted cellulose sources, it is assumed that the price of ethanol is sufficiently high that all plant sites are constructed and able to make a positive profit. Otherwise, not all sites would be constructed and continue operating. As sites are constructed to convert the total supply of materials, firms acting competitively will locate in order to minimize total costs.

The amount of dry biomass shipped between counties is designated X_{ijk}, where i is the set of counties where biomass is produced, j is the set of counties where ethanol is potentially produced, and k is the set of biomass feedstocks (corn stover and switchgrass). The relevant parameters for the cost minimization model are as follows:

p_k – production cost for biomass feedstock k ($/dry ton shipped with profit)
s_k – fixed shipping cost for biomass feedstock k ($/dry ton shipped)
f – freight rate for shipping biomass ($/dry ton shipped/mile)
d_{ij} – distance from county i to county j (miles)
C^p – added plant cost for a 50 Mgal facility (reflecting diseconomies of scale)
N – total plant capacity needed (100 Mgal/year)
l – fractional storage loss of biomass feedstock
b_{ik} – amount of biomass k produced in county i (dry tons/yr)
c_k – million gallons of ethanol per dry ton of biomass

The binary (0-1) variables I_j^{50} and I_j^{100} represent the number of 50 million and 100 million gallon ethanol plants respectively in county j, and the model is optimized by minimizing the total cost C as follows:

$$\min_{x_{ijk}, I_j^{50}, I_j^{100}} C = \sum_{i} \sum_{j} \sum_{k} \left(p_k + s_k + fd_{ij} \right) x_{ijk} + \sum_{j} I_j^{50} C^p$$

subject to:

$$\frac{1}{2} \sum_{j} I_j^{50} + \sum_{j} I_j^{100} = N \qquad (1)$$

$$I_j^{50} + I_j^{100} \leq 1 \text{ for each j} \qquad (2)$$

$$\sum_{j} x_{ijk} \leq (1-l) b_{ik} \text{ for each k and i} \qquad (3)$$

$$\sum_{i} \sum_{k} c_k x_{ijk} \geq 50 I_j^{50} + 100 I_j^{100} \text{ for each j} \qquad (4)$$

$$x_{ijk} \geq 0 \text{ for each i, j, and k} \qquad (5)$$

$$I_j^{50} = 0,1 \text{ for each j} \qquad (6)$$

$$I_j^{100} = 0,1 \text{ for each j} \qquad (7)$$

The optimization problem has several constraints. Constraints 2, 6, and 7 imply that any county can have at most one plant of either size, 100 Mgal or 50 Mgal, and that fractional plants are not permitted. Constraint 1 requires that the total amount of ethanol produced will exactly exhaust the feedstock resource base. Finally, constraints 3, 4, and 5 require that the amount of biomass supplied by a county cannot exceed the amount available from the farms in that county after taking collection/storage losses into account, and the amount of biomass supplied to each manufacturing site must be sufficient to cover the production level. The problem is implemented using GAMS version 22.5 (Brooke et al, 2005).

To determine the sensitivity of the model to biomass availability and total statewide ethanol output levels, several of the strong assumptions of the Billion-ton study are relaxed in a second application of the model, with each adjustment of assumptions resulting in lower ethanol yields for Indiana in what is considered a more conservative scenario. For instance, our base case assumes that all cropland is managed with no-till methods. When this assumption is relaxed, corn stover recovery rates drop from 70% to 52.5% (Table 3.1). Additionally, land utilization rates for the base case are assumed to be 100% whereas a rate of 75% in the second application recognizes that land owners may choose not to participate. Finally, conversion rates are decreased in the second application to reflect technical inefficiencies which are likely as manufacturing facilities begin to convert cellulosic biomass to ethanol for the first time (Tiffany, 2007).

Table 3.1 Indiana Ethanol Supply Capabilities from Major Cellulosic Sources

	Billion-ton Projection		***Conservative Estimate***	
	Corn Stover	***Switchgrass***	***Corn Stover***	***Switchgrass***
Projected yearly dry tons of biomass	9,887,958	5,348,497	6,206,723	5,348,497
Corn Stover clearance %	70%	N/A	52.5%	N/A
Land-use rate	100%	100%	75%	75%
Adjusted yearly dry tons of biomass	9,228,761	5,348,497	3,258,530	4,011,373
Storage losses	8.4%	8.4%	8.4%	8.4%
Ethanol conversion (gal/dry lb biomass)	81.4	79.0	69.7	67.6
Volume ethanol (gal/year)	688,118,569	387,038,637	208,041,476	248,574,327
Total volume ethanol (gal/year)	1,075,157,206		456,615,803	
Total ethanol assumed (gal / year)	1,050,000,000		450,000,000	

Data sources: Projections are taken from the Billion-ton study with no till methods, adjusting for a 70% corn stover harvest rate as opposed to 75%. Conservative estimates are taken from the Billion-ton study with current tillage methods, adjusting for a 52.5% corn stover harvest rate as opposed to 75%. Ethanol conversion figures are taken from McLaughlin, 1999 and Spatari, 2005 for the projects and from Tiffany, 2007 for the conservative estimate. Storage losses are calculated (see notes for Table 3.2).

Experience has shown that corn dry grind facilities are typically sized between 20 and 100 million gallons, with plants producing at or over 80 million gallons reaping most of the economies of scale associated with capital expenditures (Dale et al., 2006). On a dry cellulosic biomass input basis, there is some evidence suggesting that economies of scale might be optimized when crossing over 2,000 metric tons per day, roughly equating to 65 million gallons per year (Huang et al., 2006). The plant sizes of 50 and 100 million gallons are chosen for simplicity. Aside from the belief that these will aptly represent the low and high economy of scale regimes, the fact that 100 is divisible by 50 provides some interpretive benefits to the model. Namely, investors deciding upon a single 100 Mgal plant or two 50 Mgal plants will have to weigh the tradeoffs between the economy of scale benefits of a larger plant and the reduced transportation costs associated with distributing production sites more broadly.

Given these plant sizes, assumed conversion rates, and the resource constraints, the maximum amount of ethanol expected to be produced in the base case is 1,050,000,000 gallons per year (Table 3.1). This number is very high compared to estimates developed in other papers which apply further constraints beyond the billion-ton study based on several present day realities. The recent work of Brechbill and Tyner (2008) is one example. Using the assumptions of the second application will allow for the effects of biomass density to be tested, as 450,000,000 gallons are expected to be produced annually given the more conservative estimates of this scenario.

The costs being minimized are a combination of raw material costs, transportation costs, and economy of scale costs (the added cost of operating a small plant). Because corn stover is a residue, the cost of growing corn stover is only the marginal cost of additional fertilizer applied because of nutrients lost when the stover is removed. For the base case, harvesting, handling and storage costs are added, taking storage losses and a 15% profit premium into account, to provide a product cost of $33.68 per dry ton of shipped material (Table 3.2). Harvesting costs assume a corn stover clearance level of 70%, with 30% remaining on top of the soil past the harvest. Bales are net wrapped to minimize costs during handling. Fixed and variable transportation charges are applied at a rate of $2.20 per dry ton and $0.15 per dry ton-mile respectively. Miles are measured as the distance between the county of the farm and the county of the plant. This cost takes into account the round trip between the farm and the manufacturing facility. Similar estimates using the conservative assumptions of the second case can also be found in Table 3.2.

Switchgrass is grown as a primary crop, and therefore requires seeding and establishment costs not present for corn stover. Additionally, a land rental fee is assumed to represent the value of the land's next best alternative use. Adding these costs together with the harvest and storage costs, and assuming a 15% profit premium, results in a raw material cost of $52.95 per shipped ton. Shipping costs are then added in an identical manner to that of corn stover (Table 3.2).

Table 3.2 Raw Material and Transportation Costs for Harvested Crops and Shipped Product.

	Billion-ton Projection		*Conservative Estimate*	
	Corn Stover	***Switchgrass***	***Corn Stover***	***Switchgrass***
Seeding and establishment	0	4.51	0	4.51
Equipment cost ($/	1.86	1.31	1.86	1.31
Fertilizer/herbicide costs ($/	15.63	15.41	15.63	15.41
Harvest costs ($/ harvested	5.25	2.88	4.85	2.88
Handling costs (net wrap)	3.97	3.97	3.97	3.97
Storage ($/ harvested dry	0.11	0.09	0.11	0.09
Land rent ($/ harvested dry	0	14.00	0	14.00
Total raw material cost ($/	26.83	42.17	26.43	42.17
Storage losses (loss %)	8.4%	8.4%	8.4%	8.4%
Profit (% of raw material	15%	15%	15%	15%
p_k: Total raw material cost	33.68	52.95	33.18	52.95
s_k: Shipping costs, fixed ($/	2.1962	1.8919	2.4466	1.8919
f: Freight costs, variable ($/	0.1498	0.1498	0.1498	0.1498

Data Sources: Raw material costs for corn stover and switchgrass, as well as shipping charges and storage/transportation losses, are taken from a concurrent Purdue University working paper (Brechbill and Tyner, 2008). All costs account for residence times of harvesting, storage, and transportation.

Because transportation costs are based on the mileage between a farm in one county and a potential manufacturing site in another county, the distances between counties are required as part of the optimization problem. In this analysis, the distances between county seats are utilized as a proxy for transportation distances. Latitude and longitude coordinates were obtained for each county seat using arcGIS. Using these measures, the Haversine formula was implemented to determine the distance between county seats on the globe (Sinnott, 1984). Given that this method would produce no shipping charges for transit within a county, a distance of 10 miles is assumed for intra-county transportation.

As previously mentioned, a cost factor C^p is added for each facility, with the value equaling zero for a 100 Mgal plant and positive for a 50 Mgal plant. This factor represents the added cost of producing at a low output level and not taking advantage of the economies of scale. For instance, when producing ethanol from corn, the savings in capital expenditure is calculated to be on the order of $0.23 or greater when doubling the plant size from 50 to 100 million gallons (Tyner and Dale, 2006). Since C^p is included as an annual operating cost, it will have to be converted to a capital cost by implementing a financial analysis similar to those performed on corn ethanol plants. Specifically, what level of capital savings provides the same net present value (NPV) benefit as saving the added cost of C^p by operating at a larger level? Assumptions for the financial analysis are listed in Table 3.3.

Table 3.3 Assumptions for Financial Analysis to Annualize Economies of Scale Which Would Cover Increased Shipping Distances Associated with Larger Plant Sizes.

Assumption	***Value***
Project years	25
Start up years/operating years	2/23
1^{st} / 2^{nd} year capital investment split	40% / 60%
Investment hurdle rate (real)	8.7%

Data Sources: Assumptions taken from dry mill model (Dale and Tyner, 2006).

It is expected that if C^p is set to zero for a 50 million gallon facility (i.e., no economies of scale), that only small facilities will be used in an attempt to spread production more broadly over the state and minimize shipping distances. As C^p increases, the ideal spatial distribution of facilities should include some larger plants as the benefits of running a large scale operation would outweigh the costs of longer shipping routes. Thus, the model will be optimized over various levels of C^p to determine at what level of diseconomy of size makes it preferable to utilize larger plants, either occasionally or throughout the state.

3.4 Results

The increase in capital expenditure needed to make large plant sizes economical is modest (Table 3.4). At a total capital investment (TCI) level just under \$0.07 per gallon, at least three large plants are needed to minimize costs. Increasing TCI in very small increments results in optimized scenarios with more and more large plants until costs are minimized by operating as many large plants as possible (ten to be exact) at TCI levels of almost \$0.17 / gallon and higher.

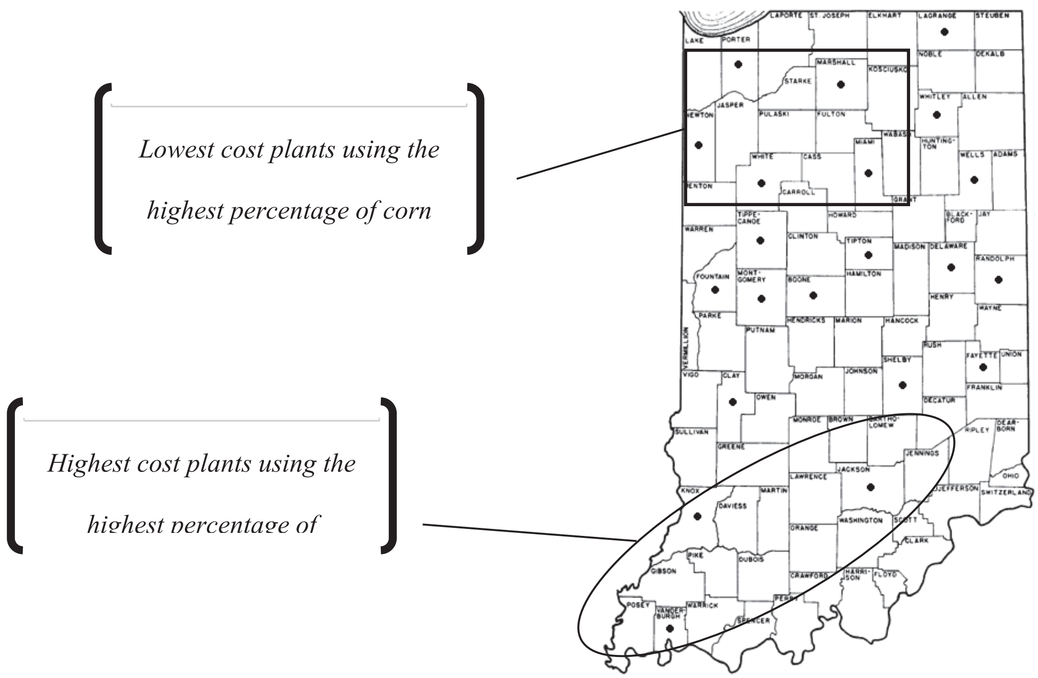
Table 3.4 Operating Cost Savings and Their Economy of Scale Equivalents Which Lead to the Transition from 50 Million Gallon Facilities to 100 Million Gallon Facilities for the Production of Cellulose Source Ethanol.

Operating costs, C_j^p (\$/gal ethanol)	Economy of scale* in capital investment (\$/gal ethanol)	Target number of 100 Mgal plants, high IN output	Target number of 100 Mgal plants, moderate IN output
\$0.000	\$0.000	0	0
\$0.003	\$0.034	0	0
\$0.006	\$0.067	3	0
\$0.009	\$0.101	5	0
\$0.012	\$0.134	8	0
\$0.015	\$0.168	10	1
\$0.018	\$0.201	10	2
\$0.021	\$0.235	10	2
\$0.024	\$0.268	10	3
\$0.027	\$0.302	10	3
\$0.030	\$0.335	10	4
\$0.033	\$0.369	10	4
\$0.036	\$0.402	10	4

*Note: Economies of scale for ethanol from corn are over \$0.23 / gallon based on scaling up from a 50 Mgal facility to a 100 Mgal facility (Dale and Tyner, 2006).

Based on this cost minimization approach, a large number of counties chosen for the biochemical production of ethanol from cellulose sources (corn stover and switchgrass) are located in the top half of the state independent of the economies of scale. As Figure 3.1 demonstrates, when no economies of scale are assumed, all ethanol is produced using 50 million gallon plants, a majority of which are located in the northern half of Indiana, with roughly one third being located in the southern half (using

Indianapolis in Marion County as an unofficial dividing line between the two halves). While the counties are spread out within regions, there are still several instances of neighboring counties having facilities, especially in the northwest region of the state. Several plant locations in the northwest tend to be the lowest cost operations in the state (Figure 3.1).



●50 Mgal plants (21)

■100 Mgal plants (0)

Figure 3.1 Optimal Counties of Manufacturing Sites for the Biochemical Conversion of Corn Stover, Switchgrass, and Poplar to Ethanol Based on Billion-Ton Study Projections and No Economies of Scale.

With respect to crop usage, there is a strong correlation between corn stover use and cost. As demonstrated by Table 3.5, which ranks the counties by corn stover use, the top five plants with respect to reducing costs all utilize the highest levels of corn stover. In fact, the ranking of cost reduction is almost identical to the ranking of corn stover usage, with plants incurring greater costs as they switch from corn stover to switchgrass.

In fact, the highest cost plants are the three plants located in the southwest portion of the state (Figure 3.1) and are the only three plants to use over 60% switchgrass.

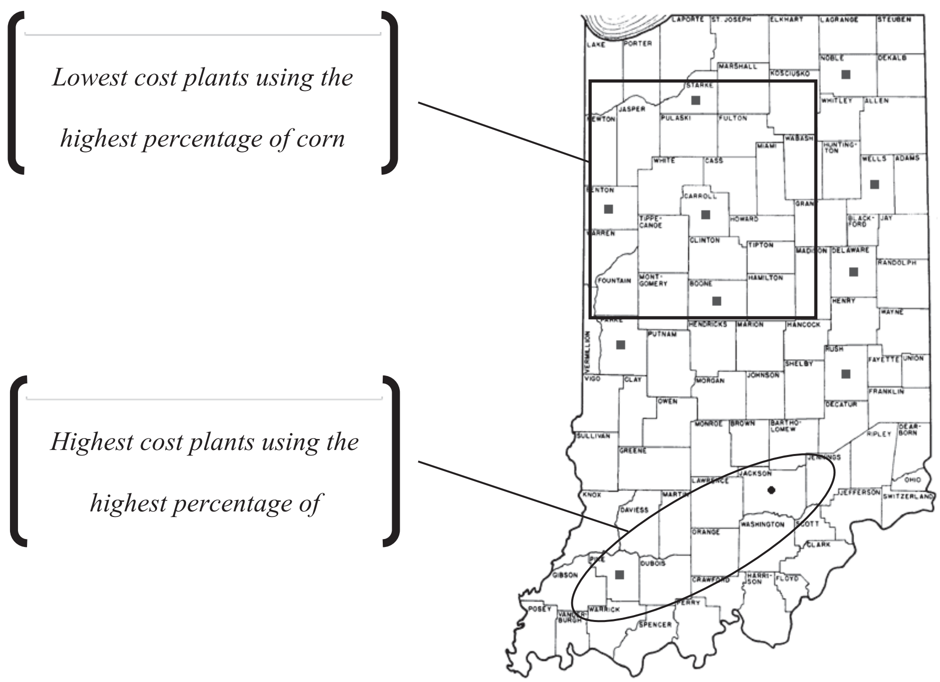
Table 3.5 Cost Ranking and Biomass Percentages for Each Plant Site Based on Cost Minimization Procedure: Billion-Ton Assumptions without Economies of Scale

Plant location	**Low cost ranking***	**% ethanol from corn stover#**	**% ethanol from switchgrass**
Marshall	2	99%	1%
Porter	4	97%	3%
White	3	97%	3%
Newton	1	95%	5%
Miami	5	94%	6%
Shelby	6	85%	15%
Tipton	7	83%	17%
Tippecanoe	8	76%	24%
Boone	9	76%	24%
Randolph	10	64%	36%
Lagrange	11	63%	37%
Montgomery	13	61%	39%
Wells	12	59%	41%
Whitley	16	51%	49%
Delaware	15	51%	49%
Fountain	14	49%	51%
Fayette	17	48%	52%
Clay	18	41%	59%
Knox	19	38%	62%
Vanderburgh	20	24%	76%
Jackson	21	24%	76%

* 1 is the lowest cost plant and 21 is the highest cost plant.
# While plants using close to 90% or higher of corn stover are likely to operate with this single input, no such restriction was placed on the model.

This trend carries over into the larger economies of scale scenario in which as many plants as possible are of the large variety (Figure 3.2). In this scenario, the top four plants in corn stover use are in northwest portion of the state. The two highest cost plants are located in the southwest and utilize significant levels of switchgrass.

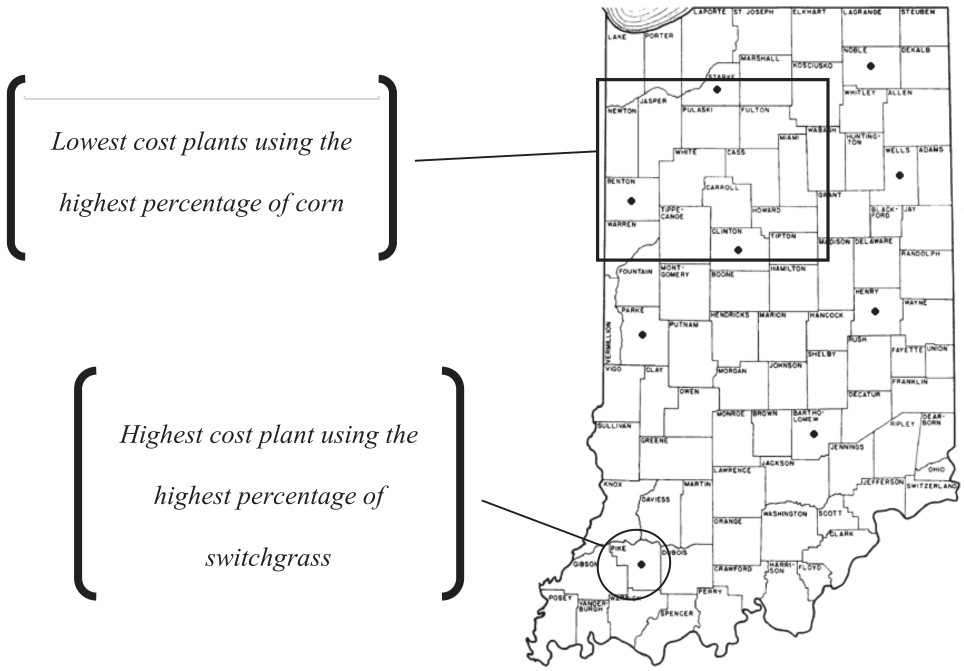
By relaxing some of the assumptions from the Billion-ton study, less cellulosic biomass is produced and collected in each county, resulting in a drop of total ethanol produced in Indiana. In this case, the highest cost and lowest cost plants are located in the same regions as the base case with the low cost plants still using mostly corn stover and the high cost plants using the most switchgrass (Figures 3.3 and 3.4). However, with the lower density of cellulosic biomass materials, greater economies of scale are required to allow for large plant sizes to be produced. While economies of scale of $0.17 / gallon ethanol allow for most plants to be converted to 100 Mgal facilities in the base case, this value only allows firms operating under conservative assumptions to consider such facilities in the low cost regions, with the full conversion to 100 Mgal facilities occurring at $0.33 / gallon ethanol (Table 3.4).



●50 Mgal plants (1)

■100 Mgal plants (10)

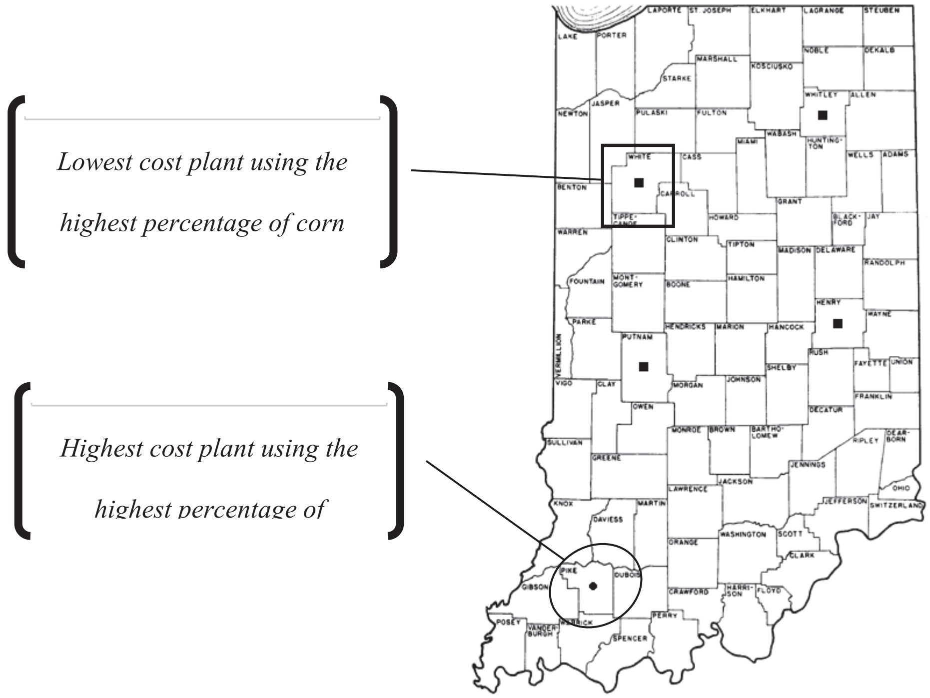
Figure 3.2 Optimal Counties of Manufacturing Sites for the Biochemical Conversion of Corn Stover and Switchgrass to Ethanol Based on Billion-Ton Study Projections and Economies of Scale.



●50 Mgal plants (9)

■100 Mgal plants (0)

Figure 3.3 Optimal Counties of Manufacturing Sites for the Biochemical Conversion of Corn Stover, Switchgrass, and Poplar to Ethanol Based on Conservative Total Yield Estimates and No Economies of Scale.



●50 Mgal plants (1)

■100 Mgal plants (4)

Figure 3.4 Optimal Counties of Manufacturing Sites for the Biochemical Conversion of Corn Stover and Switchgrass to Ethanol Based on Conservative Total Yield Estimates and Economies of Scale.

3.5 Discussion

The State of Indiana has a large potential for producing biomass sources containing cellulose, which can be biochemically converted to ethanol. This analysis optimizes the overall utilization costs of these biomass resources through the selection of optimal plant locations and sizes. However, this analysis is really a two-step optimization problem. The first step is performed by the Billion-ton study, in which land utilization is optimized based on crop potentials and current land use. For instance, since switchgrass is not a residue but a primary crop, its production requires ground preparation, seeding, and land rental fees making it more costly to grow than corn stover which is a residue of corn. Currently it would be foolish to grow switchgrass on land capable of producing corn, as both corn and corn stover can be used to produce ethanol. Therefore, switchgrass would be chosen for lands less economically suited for producing corn. These factors are taken into account in the land utilization choices of the Billion-ton study, which are therefore taken as a given, having already balanced the trade-offs between costs and benefits. While there are likely still arguments to be made for alternate land utilization strategies, they should not affect the general conclusions of this analysis.

From the analysis presented here, it is clear that current costs would dictate a high concentration of facilities within corn stover producing areas. There is ample corn stover in the northwest to support a proportionally large number of facilities, regardless of the assumptions. In areas where the land is better suited to growing switchgrass and corn stover is in short supply, raw material costs are higher due to the added costs of establishing, seeding, and renting the land. The facilities projected for two counties in the highlighted region of the southwest are prime examples, with the highest switchgrass level usage, very low corn stover farm yields, and the highest cost facilities.

If the assumed cellulosic source yields from the Billion-ton study hold true, it is likely large plant sizes of 100 million gallons or more will minimize costs. The model predicts that economies of scale for TCI above $0.17 / gallon ethanol would provide a sufficient incentive to outweigh increased shipping costs, and economies of scale for corn are at least $0.23 / gallon ethanol. Assuming that technological developments lead researchers to enzymes which can chemically break down cellulosic materials into fermentable sugars, the actual process differences between corn and cellulose conversion are (1) preparation of the material for the enzymatic conversion and (2) processing and use of the by-products. If neither of these cause large differences in the cost structures for corn and cellulosic conversion, and assuming that yields are high enough to match the Billion-ton study projections, then there likely would be more larger plants as suggested in Figure 3.2. However, another unknown is whether or not there will be diseconomies of scale due to the requirement for handling very large amounts of cellulosic materials. For example, a 100 million gallon plant with a yield of 70 gallons per ton operating 360 days per year 24 hours per day would need 3968 tons of raw material per day. Using 13 ton trucks, that amounts to over 300 trucks per day or 12 per hour (Popp and Hogan).

To the degree that the assumptions of the Billion-ton study do not hold true, the results of the conservative scenario may be more applicable for predicting the spatial distribution and size of plants. For instance, if no-till methods are not implemented or a significant proportion of land owners do not employ their land in the production and harvesting of cellulosic biomass, then economies of scale of a 100 Mgal facility may not be sufficient to cover the costs associated with the larger shipping distances which would be required to collect material. In this scenario, if economies of scale were similar to corn, it is likely that one or two large plants could be supported in the corn stover rich part of Indiana, with smaller plants filling out the rest of the state (Table 3.4).

An assumption was made pertaining to the robustness of manufacturing facilities and their ability to handle various proportions of the two major biomass sources. It may turn out that facilities are constructed to handle only a single biomass feedstock. However, this should not alter the main conclusions presented here. A firm wanting to convert only corn stover would most likely locate in the northwestern part of the state where corn stover supplies are ample, while a firm focusing on switchgrass conversion would likely locate in the south. All the crops should still be utilized based on the assumption that ethanol prices are high enough to yield any facility operator a positive profit, regardless of the crop type used. Producers utilizing higher cost crops would simply have lower profits.

Finally, the issue of naming specific counties as being “ideal” for ethanol production facilities could be misleading. Other than anticipated crop yields and distances between counties, no data was collected on any distinguishing characteristics of the counties such as infrastructure, local government incentives, or industrial zoning. A small change in raw material production costs or shipping charges could easily shift the ideal location for a facility into a neighboring county. The important conclusions here pertain to the quantity and spatial distribution of plants within certain regions of the state and the costs of operating in those regions more than the exact counties where sites might be located in the future. Additionally, as switchgrass and other primary cellulosic sources continue to be developed and optimized for the specific purpose of ethanol production, further shifts in ideal plant locations are likely to occur.

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CHAPTER 4. AN EXPERIMENTAL INVESTIGATION OF HARD AND SOFT PRICE CEILINGS IN EMISSIONS PERMIT MARKETS

4.1 Abstract

Tradable emissions permits have been implemented to control pollution levels in various markets and represent a major component of legislative efforts to control greenhouse gas (GHG) emissions. Because permits are supplied for a fixed level of pollution, allowing the market for permits to determine the price, price control mechanisms may be needed to protect firms from price spikes caused by fluctuations in the demand for permits. We test permit markets in an experimental laboratory setting to determine the effectiveness of several price control mechanisms, with special attention on the soft price ceiling. We focus on a static setting similar to some of the earliest experimental work focused on price ceilings. Results indicate that both permit supply adjustments and price ceilings (hard ceilings) effectively limit elevated prices in this setting. By contrast, reserve auctions to implement soft ceilings do not consistently control prices, especially when a minimum reserve permit price is applied. Furthermore, the grandfathering of permits allows permit sellers to realize significant welfare gains at the expense of buyers under a soft ceiling policy. Our results thus highlight several advantages of hard ceilings for controlling short term price increases.

4.2 Introduction

Emissions permit markets have been established for many pollutants to control environmental degradation. In such markets, a government supplies a fixed level of permits and firms must obtain and report permits equaling their pollution level at the time of demonstrating compliance each period. To minimize costs in a competitive emissions market, firms purchase permits at a price equal to their marginal cost of abatement, so that all firms have the same marginal cost of the last unit abated. In theory, this minimizes the total cost of achieving the target level of emissions abatement.

Price controls have been considered in many pollution markets to manage the price fluctuations of permits. Policies which introduce permits into the market at a fixed quantity corresponding to the level of pollution allowed in the market can contribute to large price volatility (Fankhauser and Hepburn, 2010). This is due to the inelastic supply of government policies that fix the permit level. Any shocks to the marginal cost of abatement will cause fluctuations in the demand for permits. Given a controlled quantity of permits, and therefore perfectly inelastic supply, any fluctuations in demand for pollution abatement are realized through adjustments to the market price and not quantity.

The purpose of price controls is to introduce elasticity in the supply curve over the range of non-zero prices, mitigating the effects of shocks or unexpected shifts in the cost of pollution abatement on permit prices. Typical controls involve the use of a price collar, which combines a ceiling and a floor. Price ceilings help firms to avoid exorbitant costs associated with price spikes due to volatility or aggressive abatement targets. Price floors stimulate investment in emissions abatement technologies in an environment where low prices provide an insufficient incentive, thus encouraging lower emissions levels in the future (Burtraw et al., 2010). Based on simulations with stochastic emissions, Fell and Morgenstern (2010) demonstrate under various banking and borrowing rules that a price collar is consistently more cost-effective than a price ceiling alone.[1]

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[1] This conclusion assumes that policies are compared for equal expected accumulative emissions. Because the price floor decreases the number of permits utilized with the price collar, simulations

In the context of greenhouse gas (GHG) legislation in the United States, various price collars have been proposed that are only differentiated by their ceilings. Each policy has a hard price floor, not allowing purchases of permits below a minimum price. The various ceilings, however, fall into one of two policy definitions: hard ceilings which set an absolute maximum on permit prices and soft ceilings which introduce a minimally priced reserve of permits into the market beyond the original target quantity. The former provides absolute price control with some emissions flexibility while the latter provides absolute emissions control while allowing prices to fluctuate beyond the soft ceiling level.

Laboratory experiments have been used to investigate a broad range of cost and price control mechanisms to manage price volatility in permit markets.[2] For example, Cason and Gangadharan (2006) find that banking diminishes price volatility in the presence of emissions shocks. However, emissions are greater when banking is allowed due to lower permit compliance rates. Stranlund et al. (2011) extend this analysis by explicitly separating compliance and reporting violations as two separate events. They find that enforcement efforts should focus on untruthful reporting since large fines applied directly to non-compliance of emissions have little effect. In either case, banking of permits allows subjects to allocate permits reasonably well over time, even in the presence of non-compliance. Stranlund et al. (2014) consider the ability of banking and hard ceilings to dampen volatility, finding that both tools are capable of individually controlling price volatility, even though the hard ceiling contributes most of the dampening effect when the two are implemented in tandem.

A broad and comprehensive set of experiments would test both hard and soft ceilings in a dynamic setting, with various combinations of banking and enforcement mechanisms, in order to compare the degree of price control in the presence of permit supply or demand shocks. However, given the limited study of the soft ceiling proposal, and the lack of any experimental research on this policy, this study begins

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testing only the price ceiling were provided with a more limited number of permits to equalize expected emissions. In this context, the higher cost induced by the price floor was outweighed by the higher cost of a more restrictive permit allotment when testing the price ceiling alone.

[2] Cason (2010) provides a comprehensive outline of various experimental evaluations of emissions permit market structures.

with a more modest goal of first understanding how the soft ceiling behaves in a repeated static environment.

Earlier research on hard price ceilings does focus on isolating within-period price effects to determine if there are any behaviors which would cause deviations from theory. For instance, a non-binding hard ceiling placed at the equilibrium price should mathematically produce the same equilibrium outcome as if there were no ceiling policy. However, researchers have found that a non-binding hard ceiling at the equilibrium price decreases transaction prices in an experimental double auction when compared to markets with no price ceiling (Isaac and Plott, 1981, Smith and Williams, 2008, Smith and Williams, 1981). This effect is strongest in the initial periods and for subjects with less trading experience, with outcomes featuring welfare shifts from sellers to buyers of permits. Coursey and Smith (1983) also confirm the presence of price depression in a posted offer market.

The soft ceiling policy is more complex than a hard ceiling, and yet there are no analogous experimental studies to determine how subjects will trade within this new environment, or how trading behavior may deviate from theoretical predictions. The purpose of this research is to begin to lay the experimental foundation for the soft ceiling. Specifically, similar to earlier research on the hard ceiling, we focus on the within-period price and welfare effects of this new policy. We find that under certain conditions, not only does the soft ceiling lack absolute price control, but prices are elevated and welfare gains from trade are transferred from buyers to sellers compared to theoretical predictions. There are also indications that splitting available permits between an initial and a reserve auction, an essential aspect of the soft ceiling policy, creates a coordination problem. Subjects do not fully account for the eventual permit allotment over both auctions, but are instead influenced by the short-term allocation before both auctions have been conducted.

The remainder of this paper is organized as follows: Section 4.3 provides detailed descriptions of both hard and soft ceilings, while section 4.4 describes how agents may trade when subjected to the soft ceiling policy. Section 4.5 provides the methodology for the study, and explains the identical theoretical outcomes between policy scenarios and the baseline treatment. Section 4.6 presents the results, with section 4.7 providing a discussion of the implications and policy recommendations.

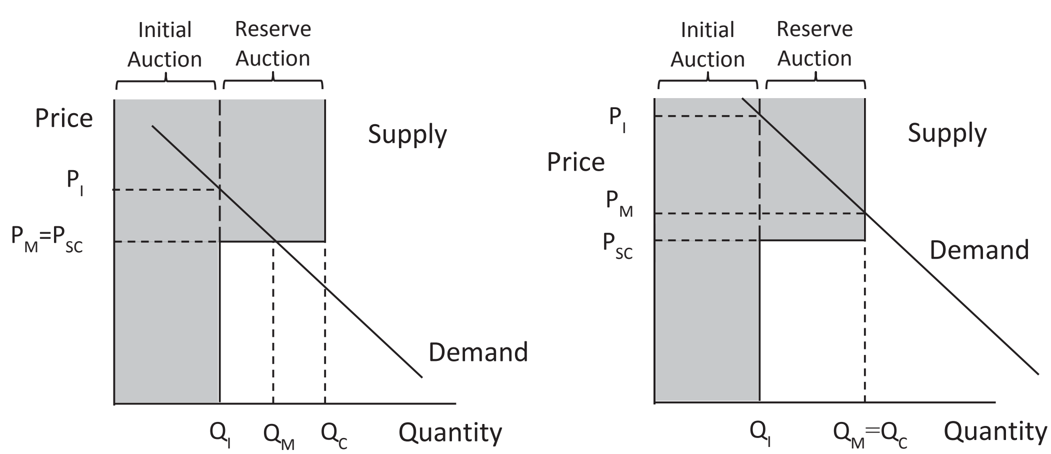
4.3 Structure of Ceiling Mechanism

A hard price ceiling is simply a price control which sets an absolute maximum value on permit prices. Assume an initial permit allotment (Q_I) with an equilibrium price (P_I). When trying to avoid prices higher than a desired maximum (P_C), a ceiling caps prices at Pc and buyers can purchase as many permits as desired at this price from an unlimited government reserve. When demand is sufficiently high such that $P_I > P_C$, the market price (P_M) will rise no higher than P_C and the market quantity (Q_M) is elevated relative to the initial permit allotment (Q_I). In such a situation, the price ceiling is binding, working effectively as an emissions tax (t) with $t = P_C$. By implementing perfectly elastic supply, a hard ceiling places utmost importance on controlling prices at the expense of releasing as many permits as required into the market to keep prices below the ceiling. A notable example of such a price ceiling in Federal GHG legislation was proposed by Senators Cantwell and Collins (Cantwell, 2009) as part of the Carbon Limits and Energy for America's Renewal (CLEAR) Act. This act proposed a hard price ceiling with scheduled annual increases set automatically as a function of the real discount rate.

By contrast, the soft price ceiling does not set an absolute upper limit on the price of permits. In fact, the term "soft price ceiling" is not a ceiling by definition, but the terminology we utilize for a reserve auction of permits with a minimum reserve price as desribed by Murray, et al. (2009). Fell et al. (2012) have employed the term "soft collar" when analyzing the effectiveness of a reserve auction in comparison to a hard collar with an absolute maximum price. Such a reserve auction was passed in the House of Representatives as part of the permit trading market proposed in H.R. 2454 by Congressmen Waxman and Markey (Waxman and Markey, 2009). Slightly different structures have been proposed in other policy initiatives, including a contingency reserve of unsold allowances which could be a triggered by a soft ceiling as part of the Regional Greenhouse Gas Initiative (Burtraw et al., 2007) and a more complicated variant with three price tiers established in the California GHG permit trading scheme (Pavley and Nunez, 2006).

In a permit market with a soft ceiling (Figure 4.1), an initial quantity of permits (Q_I) is introduced to the market equal to desired emissions levels. In the absence of additional permits or controls, the equilibrium price for this initial allotment would occur at P_I. At the time when permit holders are expected to demonstrate compliance, an additional quantity of permits called the allowance reserve is offered at auction with a minimum reserve price (P_{SC}), potentially allowing those with insufficient permits to make up for their shortage. The aggregate of the initial and reserve auction permits represents a quantity control on the total market (Q_C). The introduction of reserve permits as described by Murray et al. (2009), as well as Waxman and Markey's legislation, is not induced by a price trigger but is provided automatically every period. Firms are not bound by the soft price ceiling in the initial auction and will have reserve permits available regardless of trading prices earlier in the period.

(a) Demand intersects supply at soft ceiling (b) Demand intersects supply above soft ceiling



(Shaded regions represent allowable trades.)

Figure 4.1 Controlling High Prices with a Soft Ceiling

The soft ceiling (P_{SC}) receives its name from the intended impact of the minimum reserve price on the market price for permits (P_M) by introducing supply elasticity as represented by the horizontal section of the supply curves in Figure 4.1. If demand were to intersect supply such that $P_I < P_{SC}$, the market price would be equal to P_I and none of the reserve would be purchased. As demand increases, P_M increases until $P_M = P_{SC}$ (Figure 4.1a). Under such conditions, firms perfectly coordinating prices across auctions would purchase permits at the minimum reserve price. In this way, while there is no absolute maximum, the horizontal portion of supply acts as a kind of soft ceiling over a range of demands. As demand continues to increase, however, the market price would eventually rise above the soft ceiling when the reserve allotment is exhausted (Figure 4.1b). Nonetheless, prices would still be lower than if there were no reserve at all. This design is appealing to policy-makers primarily concerned with climate change because unlike hard ceilings it allows for an absolute cap on emissions (Q_C), while still providing some, although not absolute, control of prices.

4.4 Expectations in a Repeated Static Environment

Non-experimental studies comparing the effects of hard and soft ceilings on prices and total emissions are limited. A macroeconomic analysis of proposed legislation predicts that permits in the initial market would be purchased at the ceiling price for many years in order to bank permits in expectation of higher future prices (Williams, 2010). Fell et al. (2012) perform a dynamic numerical analysis, comparing the two mechanisms with banking of permits available. When targeting identical cumulative emissions goals in the presence of shocks to baseline emissions levels, they find the intuitive result that the hard ceiling decreases price volatility more than a soft ceiling, and the hard ceiling level required for emissions parity with the soft ceiling is higher. [3] While such findings are helpful for policy-makers in determining the optimal level and pathway for price ceilings, they do not address the behavior of individual agents who may deviate from theoretical assumptions of how optimization occurs within a single period of the price discovery process. There are many types of behavior which could cause markets to deviate from the competitive equilibria described in Figure 4.1, in which costs are minimized by balancing marginal costs with the price of permits across both the initial and reserve auctions. Large deviations could introduce potentially significant consequences with respect to controlling prices.

For instance, if agents in the initial auction were to ignore reserve auction permits altogether, and thus price permits based on the initial auction only, one would expect initial auction prices to equilibrate close to P_I. One of the earliest emissions permit auctions, which regulated SO_2 levels under the Clean Air Act, demonstrated that the spot market was more heavily influenced by current market conditions and not the anticipated future auction of additional permits (Burtraw et al., 2011). While this factor may play a role in elevating prices during the earlier periods, the repeated static nature of the experiment should allow agents to gain experience and more successfully equilibrate across auctions in later periods as compared to a dynamic setting.

Another factor which could cause prices to deviate from the competitive equilibrium is market power. Buyers with market power wanting to avoid prices above the floor of the reserve auction could withhold demand to depress prices in the initial auction while sellers with market power wishing to hold out for the reserve would tend to increase prices. In this set of experiments, as well as for the beginning years proposed in the Waxman-Markey legislation, sellers could maintain market power due to extensive grandfathering of permits. Goeree et al. (2010) study the impacts of grandfathering vs. auctioning initial permit allotments before a single-round, limit-order call market. Agents with large grandfathered permit allocations strategically withheld permits from the market, generating elevated prices in

[3] Fell et al. (2012) study a price collar, which provides a hard price floor in the initial auction in conjunction with either a hard or soft ceiling.

comparison to both the theoretical equilibrium and the allotment by auction. Sellers could exercise similar market power in our experiment, exacerbating the resulting price elevation above the price floor in the reserve market.

Finally, we expect price increases from the floor of the reserve auction to be further augmented based on past experimental studies of bidding behavior in the presence of price floors and ceilings. In the context of a double auction, Smith and Williams (1981) found that a hard price floor elevated bids of both buyers and sellers in comparison to non-bound theoretical equilibria at or in close proximity to the price floor. Sellers with market power able to observe this behavior could construct higher price expectations for the reserve and revise their bids in the main auction upwards as a result. For these reasons, we would expect prices to be elevated, and therefore not controlled, compared to the theoretical equilibrium.

4.5 Methodology

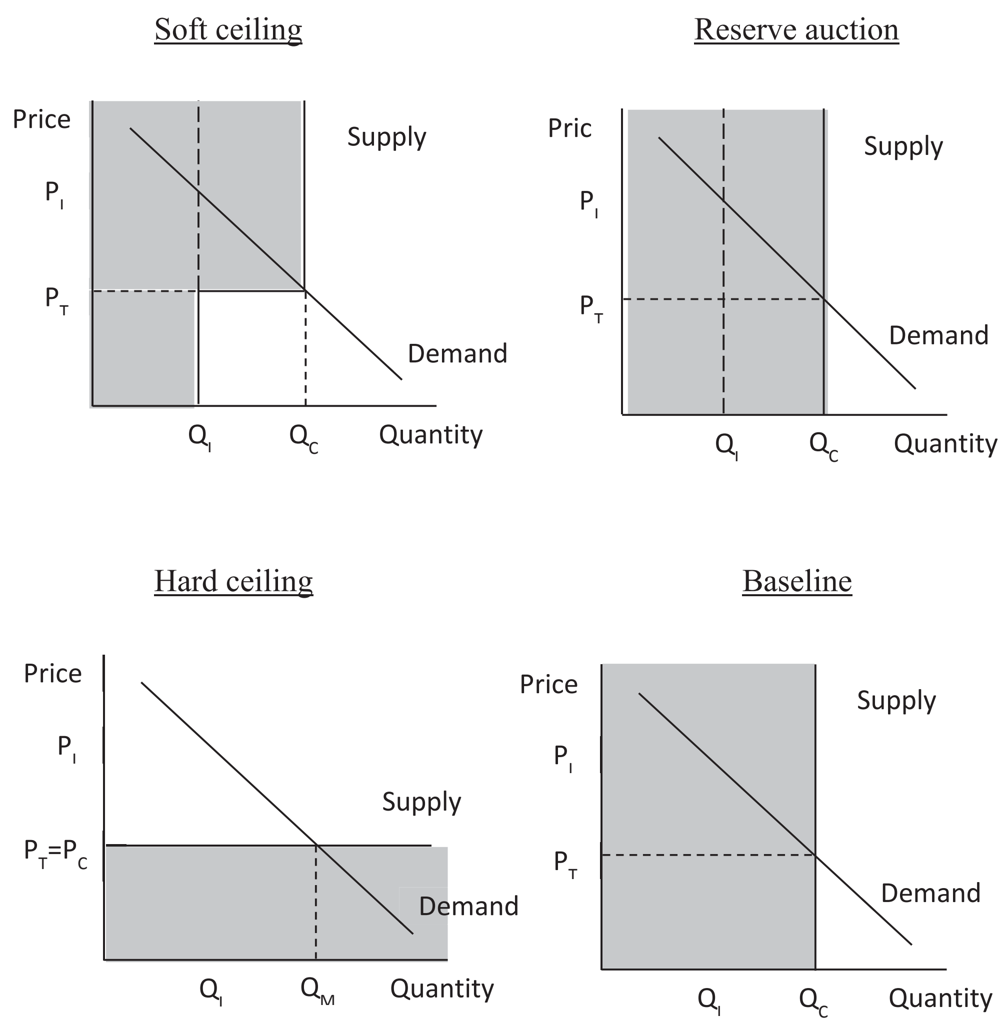
We use an experimental laboratory setting to compare the ability of soft and hard price ceilings to control prices. To isolate the impact of the soft ceiling, we consider stationary repetition of identical single period environments (i.e., no banking or borrowing of permits) and adjust only the price control mechanism across treatments.

We conduct 16 experimental sessions across four treatments consisting of a soft ceiling, a reserve auction with no soft ceiling reserve price, a hard ceiling, and a baseline with no price controls or reserve allocation for comparison. Figure 4.2 depicts the four policy choices tested. In each case, an initial auction of Q_I permits yields an equilibrium price of P_I, with $P_I > P_T$ and P_T denoting the target maximum price in the auction for permits. Each policy targets the same price, quantity combination such that any differences in actual price outcomes are caused by subject behavior and not policy targets. Starting in the upper left-hand corner of Figure 4.2, we test the soft ceiling, defined as a reserve auction with the key structural components outlined in Waxman and Markey, a reserve floor price and substantial grandfathering of permits (Soft ceiling). Moving clockwise, we test the same structure, but relax the minimum price floor in the reserve auction, thus eliminating the soft ceiling (Reserve auction). We then test increasing the quantity to the same total cap (Q_C) as the first two policies, but in a single auction without the use of a reserve auction (Baseline), providing a control for the other treatments. Finally, we test a hard price ceiling (P_C) where the ceiling price equals the target price of the other three policies (Hard ceiling). Due to its straightforward nature, the hard ceiling treatment was conducted in only 1 of the 16 sessions, which allowed us to confirm that prices readily converged to the ceiling price and to dedicate experimental earnings more heavily towards the other treatments.

We employed 8 subjects per session for a total of 128 subjects recruited from the population of undergraduate students at Purdue University with no prior experience in experiments related to emissions permit markets. In addition to a $5.00 show-up fee, subjects earned experimental dollars which were converted immediately to U.S. Dollars at the conclusion of their experimental session. Average total earnings were $26.69, with a standard deviation of $6.37.

Subjects were provided the opportunity to manage a firm with an existing level of pollution and a fixed revenue stream. They were incentivized, through monetary payments, to minimize costs while accounting for all pollution through some combination of abatement and permit purchases. While this research focuses on pollution abatement, subjects did not view any environmental terminology. For example, the level of abatement of pollution was written as "units of an experimental good produced" and emissions permits were called "coupons." All experiments were conducted over a computerized network, with subjects interacting in markets through a client interface programmed in Z-tree (Fischbacher, 2007).

For each session, 8 subjects participated in 14 identical and separate periods, the first 2 of which were practice with no payment. Within each period, all subjects were required to abate up to 10 units of pollution with increasing marginal costs of abatement or obtain permits to substitute for pollution not abated. At the end of each period, the sum of permits held and pollution abated were required to equal 10 under a rule of automatic compliance. Each subject had a unique set of marginal costs, which when aggregated together determined the market demand for permits as illustrated in Figure 4.3.



(Shaded regions represent allowable trades.)

Figure 4.2 Four Policy Treatments Tested as Price Controls in an Experimental Market.

For all treatments, 40 permits were distributed to the market in each period, with half being distributed before the initial auction and half before the reserve auction. (The one exception occurred in the Baseline treatment in which all permits were distributed before a single auction.) While a typical soft ceiling design would likely distribute a smaller proportion of the permit allotment in the reserve, we distributed 50% in order to increase the disparity between equilibrium prices with and without the reserve, and thus magnify behavioral effects on prices in our experimental market setting. The predicted equilibrium price in the initial auction is $123. A successful price control would decrease the price in the initial auction down to a new equilibrium of $85 as shown in Figure 4.3.

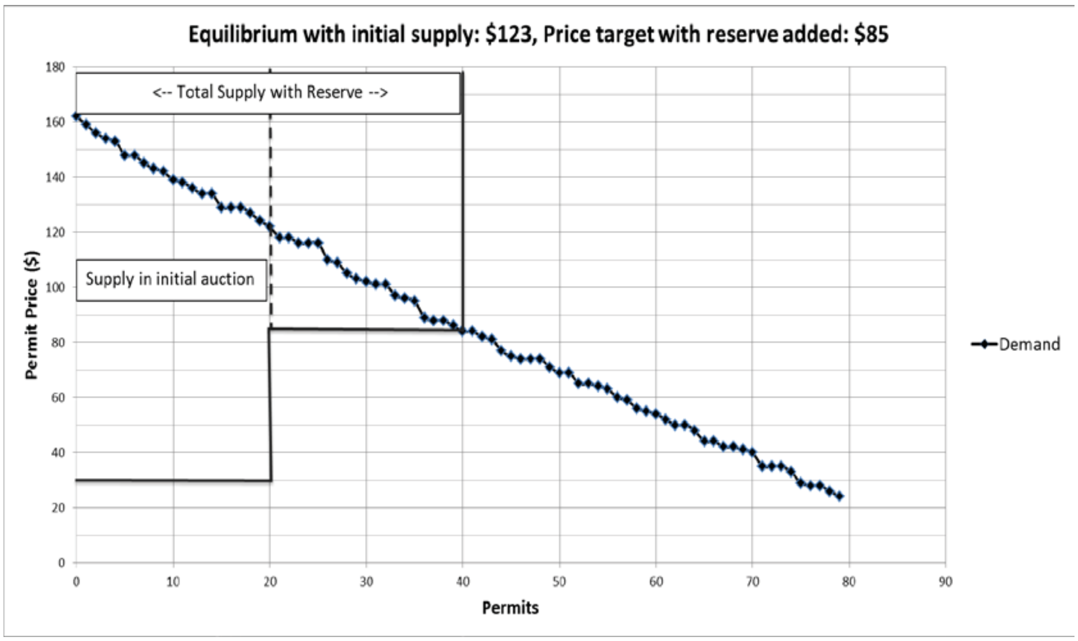


Figure 4.3 Demand and Supply for Permits in Emissions Market (Soft Ceiling).

After initial permits were allocated, subjects were free to purchase and sell permits with each other in a double auction. We used this method to simulate the heavy grandfathering of permits built into the early years of the Waxman and Markey legislation. We utilized a continuous double auction trading institution similar to Cason and Gangadharan (2006) in which any subject could continuously make or accept single permit price bids for both selling and purchasing of permits. Experimental instructions for all treatments are provided in the appendices. We posted all price ceilings and floors at the top of the screen during trading, both for the initial auction and the future reserve auction when applicable.

After completing the initial auction, reserve permits were distributed (except for the baseline treatment which ended at this point in each period). Subjects then traded permits again using a double auction similar to the first phase of the period. We used the same trading procedures after grandfathering reserve permits for two reasons: (1) the auction format already placed a high level of cognitive demand on subjects, and learning two completely different auction formats would have added unnecessary complexity; and (2) substantial grandfathering of permits is common during initial years of many permit trading schemes in the field. For both the initial and reserve allocations, permits were heavily distributed towards the 4 lowest cost abaters to induce a high volume of trading and create liquid markets.

4.6 Results

We have implemented four treatments designed to achieve equal emissions levels and target the same equilibrium price in order to determine the effectiveness of a soft and hard ceiling in maintaining a maximum price. We test a hard ceiling treatment, a soft ceiling treatment, as well as a reserve auction only treatment against our control, the baseline treatment in which the reserve amount is added to the initial auction, and the target equilibrium price.

4.6.1 Prices in the Main (Initial) Auction

Result 1: The hard ceiling controls prices, with market prices converging closely to the target equilibrium price.

Support: Figure 4.4 displays the mean trading prices, indicating that the hard ceiling price quickly approaches the maximum target of \$85 by the eighth period and averages \$84.6 over the final five periods. Since the hard ceiling effectively achieves the objectives of controlling the price at the target, this treatment serves as a useful benchmark against which to evaluate other treatments.

Figures 4.4 and 4.5 demonstrate that the hard ceiling treatment price converges on the target of $85.0, with the average market price in the final two periods equaling the ceiling price exactly. Past research assessing price ceilings in experimental markets has demonstrated eventual convergence of price with the ceiling under certain conditions, with more experienced subjects converging more quickly (Isaac and Plott, 1981). Our subject pool was drawn from students with no experience in emissions permit markets, and showed convergence speed commensurate with inexperienced subjects in other studies.

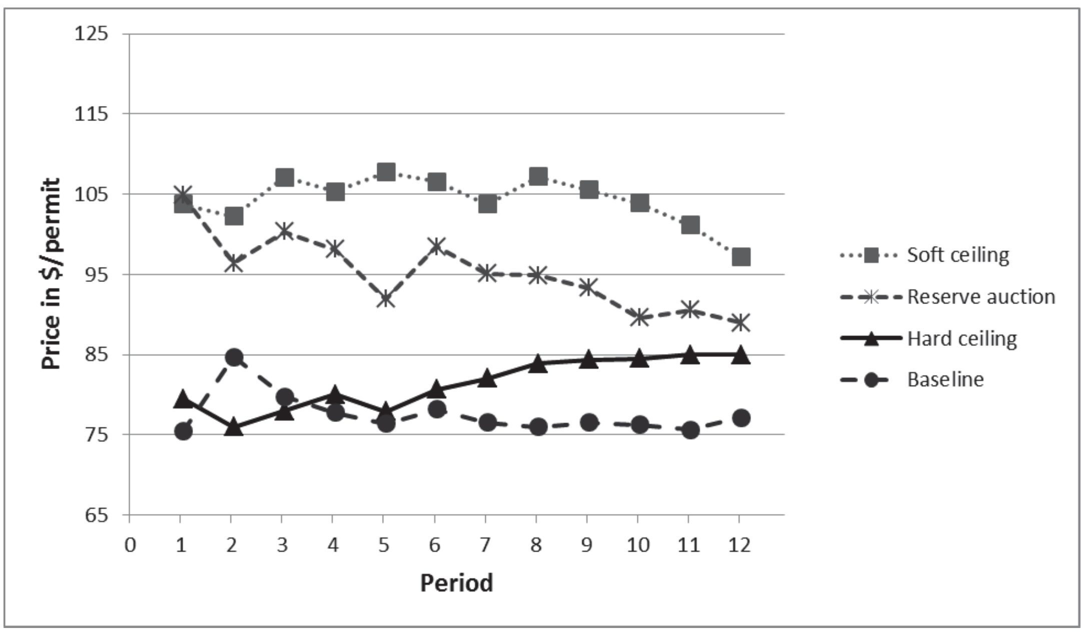


Figure 4.4 Mean of Last 8 Trades in Initial Auction for Each Period (All Sessions)

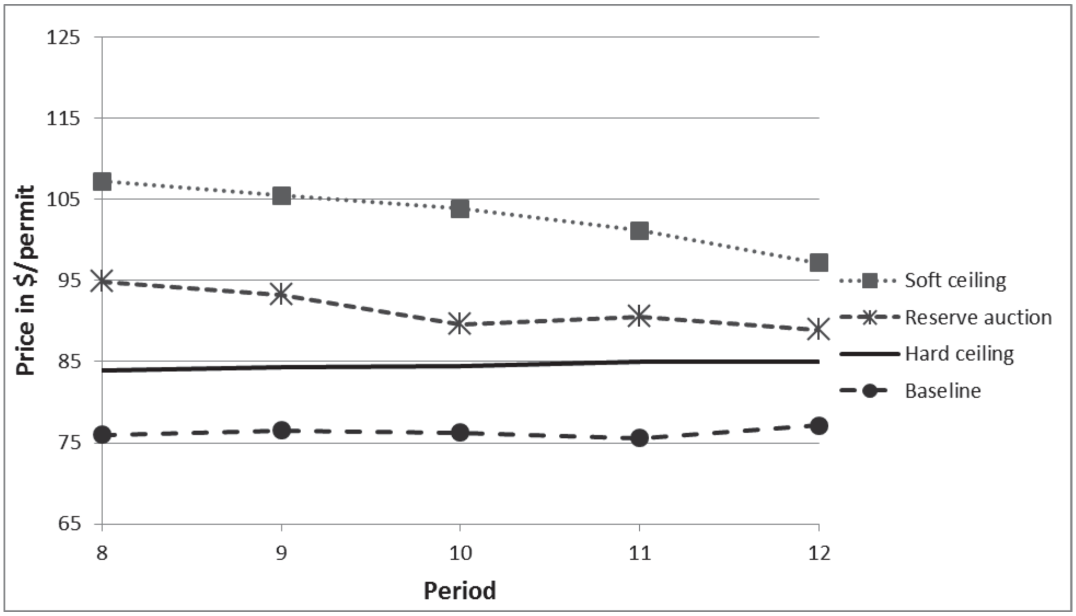


Figure 4.5 Mean of Last 8 Trades in Initial Auction for Last 5 Periods (All Sessions)

Result 2: In the baseline treatment with no price controls, prices attain the equilibrium price when the entire permit supply is provided in a single auction.

Support: Table 4.1 reports Wilcoxon Signed Rank tests, a non-parametric test which compares the average initial auction price over the last 5 periods for each session to the target equilibrium price (85). For the baseline treatment this test does not reject the null hypothesis that mean prices equal the equilibrium level.

Table 4.1 p-Values for Main Auction Treatment Comparison[a]

(Non-Parametric Mann-Whitney Test and Wilcoxon Signed Rank Test[b])

Treatment	**Soft Ceiling**	**Reserve Auction**	**Baseline**
Mean price, $/permit (std err)	103.0 (2.9)	91.5 (8.8)	76.3 (4.5)
vs. Reserve Auction	0.548		
vs. Baseline	0.008***	0.310	
vs. Equilibrium (85)	0.062*	0.438	0.188

a Session means based on final 8 trades of initial auction over each of the last 5 periods.
b The Wilcoxon Signed Rank Test is only used for comparisons to equilibrium.
* significant at 10%
***significant at 1%

While non-parametric tests utilize data from the last 5 periods of each session, such tests do not differentiate data between periods. Therefore, any information regarding experience gained and its impact on mean and error correlations across periods is lost. Additionally, information from the first 7 periods is excluded. Given the visual evidence in Figures 4.4 and 4.5, which indicates that prices may still be decreasing slightly over time for the reserve auction and soft ceiling treatments, it is desirable to adopt a model which can differentiate estimates of prices in the initial auction for each period. Specifically, we adopt a model introduced by Noussair et al. (1995) and utilized in several applications to test for convergence of adjusting prices in experimental markets (Cason and Noussair, 2007). For each treatment i, Table 4.2 provides estimates for the mean price in the main auction for the first period with no experience (β_{i1}), for the end of session period based upon the price to which the model converges with maximum experience (β_{i2}), and for the change in price over the course of the experiment. The model is specified as follows:

$$\text{Price}_{jt} = \left(\sum_{i=1}^{n} \left(\beta_{i1} D_i (1/t) + \beta_{i2} D_i (1 - 1/t) \right) \right) + \varepsilon_{jt} ,$$

where i indexes the treatment, j indexes the session, t indexes the period,

$\text{Price}_{jt} \equiv$ mean of the last 8 prices of the initial auction in period t, session j,
$\beta_{i1} \equiv$ the parameter for the starting price in treatment i,
$\beta_{i2} \equiv$ the parameter for the asymptotic price outcome in treatment i,
$D_i \equiv$ the dummy variable for treatment i, and
$\varepsilon_{jt} \equiv$ the error term for session j in period t.

This model accounts for the time pattern of prices using the terms (1/t) and (1 – 1/t). In the first period when t = 1, (1 – 1/t) = 0 and 1/t = 1 so β_{i1} provides an estimate for the price at the start of the markets for treatment i. As t grows larger, (1/t) $\rightarrow$ 0 so β_{i2} provides an estimate for the price outcome approached in the limit for treatment i as t $\rightarrow \infty$.

Accounting for interdependencies between periods within each session requires the use of panel data regression methods. We define each of the 15 experimental sessions (excluding the single session testing the hard price ceiling) as a data cluster. A generalized linear model procedure is employed which provides robust standard errors based on an autoregressive structure to account for correlated errors within each session.

Table 4.2 Estimates of the Mean Price in the Main Auction for the First Period (β_{i1}, t = 1), the End Period ($\beta_{i2,}$ t → ∞), and the Change Across Periods[a,B]

$$Price_{jt} = \beta_{11}D_1(1/t) + \beta_{12}D_1(1-1/t) + \beta_{21}D_2(1/t) + \beta_{22}D_2(1-1/t) + \beta_{31}D_3(1/t) + \beta_{32}D_3(1-1/t) + \varepsilon_{jt}$$

Treatment Parameter	**β_{i1}, t = 1**	**β_{i2}, t → ∞**	**β_{i2} - β_{i1}**
	Mean Price ($/permit) test vs. equilibrium[c]	Mean Price ($/permit) test vs. equilibrium	Price Change ($/permit) test vs. 0
Soft ceiling	103.1 (2.1)	102.1 (2.4)	-1.0 (2.9)
($\beta_{1.}$)	< 0.001***	< 0.001***	0.733
Reserve auction	104.4 (6.9)	90.6 (8.4)	-13.8 (5.4)
($\beta_{2.}$)	0.005***	0.506	0.010***
Baseline	70.7 (3.0)	81.4 (4.4)	10.7 (5.9)
($\beta_{3.}$)	< 0.001***	0.414	0.069*

a Mean prices and price changes are provided with standard errors in parentheses and p-values below.
b Robust standard errors are assumed based on session level clusters with an autoregressive correlation structure.
c p-values for estimates of the mean price are for tests against an equilibrium price of 85.
* significant at 10%
***significant at 1%

Table 4.2 shows that the baseline treatment β_{i2} estimate for asymptotic prices (t →∞) is 81.4, which is not significantly different from the equilibrium prediction of 85 (p-value=0.414). With experience, we cannot reject that subjects achieve the competitive equilibrium.

Result 3: The reserve auction alone appears to control prices to equilibrium after subjects have had time for price discovery. However, prices are elevated above equilibrium at the beginning of the price discovery process.

Support: For the Reserve Auction treatment, Table 4.1 shows a comparison of mean prices averaged over the last 5 periods for each session to the equilibrium prediction of 85 using the Wilcoxon Signed Rank test and to the baseline treatment using the non-parametric Mann-Whitney Test. No significant difference in the main auction prices is detected when compared to the equilibrium or the baseline treatment. The asymptotic price estimate of 90.6 (Table 4.2) can also not be rejected as being equivalent to the equilibrium price (p-value=0.506) or the baseline treatment (p-value=0.333, Table 4.3).

In the early periods of the reserve auction treatment, prices are elevated (104.4) compared to the equilibrium (Table 4.2), rejecting the null hypothesis that first period prices equal the target price of 85 (p-value=0.005). As subjects gain experience, the prices decrease significantly (p-value=0.010) to 90.6. Thus, while the reserve auction alone does not provide absolute control of prices over all periods, it yields prices that are not significantly different from the competitive equilibrium once subjects have gained experience across trading periods.

Table 4.3 Comparing Estimates of the Main Auction Mean Price across Treatments (β_{i2}, $t \rightarrow \infty$)[a]

Treatment	**Soft ceiling**	**Reserve auction**	**Baseline**
Mean price, $/permit (std err)	102.1 (2.4)	90.6 (8.4)	81.4 (4.4)
vs. Reserve auction	11.6 (8.7)		
	0.186		
vs. Baseline	20.7 (5.0)	9.2 (9.5)	
	< 0.001***	0.333	

a Differences between means are provided with standard errors in parentheses and p-values below.
***significant at 1%

The reserve auction treatment increases the complexity of the baseline in that cost minimization efforts must be balanced across two separate auctions. These results indicate that for experienced subjects, we cannot reject the hypothesis that the reserve auction can effectively control prices in the main auction.

Result 4: The soft price ceiling does not control prices as intended in the main auction. Prices are above equilibrium for both early and late periods.
Support: Non-parametric tests reject the null hypotheses that the soft ceiling price is equivalent to either the equilibrium price or the baseline treatment price (Table 4.1). Price estimates of the soft ceiling design are significantly elevated above the equilibrium price both for early and late periods (Table 4.2). The null hypothesis that prices are equal to the baseline treatment (Table 4.3, p-value < 0.001) is clearly rejected. Price estimates also do not change significantly over time (Table 4.2, p-value = 0.733).

4.6.2 Session Price Trends and Reserve Auction Prices

The data indicate that the hard ceiling controls prices in the main auction to the competitive equilibrium while the soft ceiling does not. However, there is still some uncertainty regarding how well the reserve auction alone actually controls prices, even though we cannot reject price control for this treatment. Recall from Table 4.2 that no statistically significant difference exists between prices in the main auction and the equilibrium price in either the baseline or the reserve auction only treatments. When analyzing transaction prices in individual sessions for each of these two treatments, some have prices predominantly below equilibrium while some have prices predominantly above. Only in the soft ceiling treatment do we observe average period prices consistently above the equilibrium price for all sessions. Therefore, the ability of sellers to consistently trade permits above equilibrium in the main auction must be attributable to the reserve auction having a price floor as in the soft ceiling design.

Result 5: The minimum reserve price of the soft ceiling increases trading prices in the reserve auction.

Support: Table 4.4 reports price estimates generated for the reserve auction using the same regression techniques as in the main auction. Reserve prices with a floor in the soft ceiling design are 96.0, significantly higher than equilibrium (p-value < 0.001). Reserve prices without a floor were not significantly different than equilibrium (p-value = 0.818).

Given that sellers receive better prices in the reserve auction and consistently better prices in the main auction with the soft ceiling design, it is useful to determine whether higher prices translate to improved welfare outcomes for sellers.

Table 4.4 Estimates of the Mean Price in the Reserve Auction ($\beta_{i2,}$ t → ∞) and Comparison to Equilibrium[a]

Treatment	Soft ceiling	Reserve auction only
Mean price, $/permit (std err)	96.0 (2.1)	86.7 (7.3)
vs. Equilibrium (85)	11.0 (2.1)	1.7 (7.3)
	< 0.001***	0.818

a Differences are provided with standard errors in parentheses and p-values below.
***significant at 1%

4.6.3 Welfare Gains from Trade

Recall that permits were more heavily allocated to the 4 traders with low marginal costs of abatement in order to create a thicker market. Such traders became net sellers of permits while the other 4 traders with small initial permit allotments became net buyers. For each period, a subject's welfare gains are calculated as:

Revenue from permits sold – Marginal abatement costs realized from selling permits

– Cost of permits purchased + Marginal abatement costs avoided from buying permits

Welfare gains differ from total profits in that they do not include fixed period revenues or initial abatement costs before trading. Thus, welfare gains are completely determined by the trading decisions of subjects.

In an efficient market for this experimental environment, net buyers would purchase enough permits at the equilibrium price (85) to avoid any marginal abatement costs above this price. Similarly, net sellers would sell enough permits at the equilibrium price to incur any marginal costs below this price. The theoretical welfare gains for such an efficient market can be calculated for the aggregate of net sellers and net buyers separately. The proportion of efficient welfare gains realized is determined by calculating the ratio of actual realized welfare gains to theoretical efficient welfare gains. Note that this proportion can be greater than 1. For instance, if net buyers are able to consistently purchase permits below the equilibrium price, they could realize welfare gains greater than the efficient level at the expense of net sellers.

Result 6: The soft ceiling policy allows net sellers of permits to realize greater welfare gains than efficient levels at the expense of net buyers.

Support: The same regression model and panel data methods used to analyze prices are also used for welfare analysis, with the proportion of efficient welfare gains replacing average price as the dependent variable. We are interested in the end period welfare gain estimates corresponding to the auction price estimates in Tables 4.3 and 4.4 (β_{i2}, $t \rightarrow \infty$) after subjects have gained experience. Table 4.5 shows that under the soft ceiling, net sellers realize welfare gains 1.31 times the efficient level based on the asymptotic estimate for this model. This is consistent with the high prices observed for this treatment and significantly different at the 5% level and 1% level than the proportions for the reserve auction (0.87) and baseline (0.82) treatments respectively.

As deadweight losses for the soft ceiling are not statistically different than the other two treatments (ranging from 0.14 to 0.20), this large welfare gain occurs at the expense of net buyers, who realize a gain of only 0.5 times their efficient level.[4] This low realized gain for net buyers in the soft ceiling treatment is significantly different at the 1% level from the proportions for the baseline (0.91) treatment.

Table 4.5 Comparison of Welfare Gains from Trade for End of Session (β_{i2}, $t \rightarrow \infty$)[a]

Treatment	Soft ceiling	Reserve auction	Baseline
Proportion efficient gain (std err) Sellers	1.31 (0.05)	0.87 (0.21)	0.82 (0.12)
Difference vs. soft ceiling		-0.44 (0.22)	-0.49 (0.13)
Sellers		0.044**	< 0.001***
Proportion efficient gain (std err) Buyers	0.50 (0.07)	0.74 (0.14)	0.91 (0.05)
Difference vs. soft ceiling		0.24 (0.16)	0.41 (0.09)
Buyers		0.139	< 0.001***

a Differences between means are provided with standard errors in parentheses and one sided p-values below.
** significant at 5%
***significant at 1%

4.7 Discussion

A hard ceiling provides an absolute maximum for prices, allowing the number of permits, and therefore the amount of emissions, to increase as much as needed when prices hit the ceiling. Some scientists, economists, and policy-makers have advocated for reserve auctions and soft ceiling designs, which have the desirable property of placing an absolute cap on emissions levels, while still providing some

[4] Deadweight losses are a proportion of efficient welfare gains from trade that go unrealized, and are considerably smaller when reported as a proportion of efficient total profits.

level of price control. A hard price ceiling could increase emissions considerably if the market price consistently hits the ceiling.

We have demonstrated that while a hard price ceiling can act as an effective price control, the soft ceiling fails to control prices to theoretical predictions under the conditions of our experiment. The evidence points to the presence of the minimum reserve price as the culprit for elevated prices in the main auction. The grandfathering of permits, in conjunction with the guaranteed minimum price in the reserve auction, allows net sellers to strengthen negotiating power in this multilateral trading institution, which translates to higher trading prices and greater welfare gains to sellers.

Previous research has also shown that the grandfathering of permits elevates prices compared to the direct auctioning of permits by the government (Goeree et al., 2010). In the reserve auction without a price floor, traders eventually converged on the equilibrium price. When the price floor was introduced, prices remained significantly higher than equilibrium. This is partly due to the nature of the soft ceiling, which does not allow for price deviations below the equilibrium in the reserve auction. Interestingly, the elevated prices carried over into the main (or initial) auction even though it places no restrictions on prices. By contrast, when the reserve had no minimum price, we observed some sessions in which sellers traded below equilibrium in the main auction and some in which they traded above. Sellers were not able to consistently elevate prices without the guarantee of the minimum reserve price. As a result, only in the soft ceiling treatment did sellers achieve significant welfare gains at the expense of buyers.

Another concern relates to elevated prices in the main auction for inexperienced subjects. We observed such price increases for both reserve auction treatments, regardless of the presence of a minimum reserve price. From the data, it cannot be determined whether high prices are due to inexperience with the trading mechanism or inexperience with the static demand and supply conditions in the market. If the latter contributes in any way, this would further hinder the ability of the soft ceiling to control prices in a dynamic setting.

Our results raise serious concerns regarding legislation that combines a soft ceiling design with the grandfathering of permits. This design is not an absolute price control in theory, and our results indicate that it actually elevates prices compared to theoretical predictions. If absolute price control is the primary goal, a hard ceiling would be preferred. Alternatively, if the reserve auction is desired to control the absolute level of admissions, eliminating the minimum reserve price or the grandfathering of permits would be beneficial to controlling prices, although more study is required for verification.

An alternative policy not studied here could provide the best of both worlds. Such a hybrid policy would utilize a hard price ceiling for short term price stability, and the ceiling level could be adjusted periodically to achieve cumulative emissions targets. Unlike other pollutants which may be toxic based on flow levels to the environment within each period, the deleterious nature of greenhouse gases is determined by stock amounts within an ecological system. This affords regulators utilizing a hard ceiling system the flexibility to manage greenhouse gas levels across periods without extreme concern for emissions spikes within a given period. In such a system, quantity control adjustments of the hard price ceiling could replace the discount rate adjustments currently proposed in most legislation. The rule for making adjustments should be well-defined and clearly communicated so as not to introduce additional uncertainty to permit markets.

A similar approach has been recommended by Metcalf (2009) for emissions taxes, with the tax adjusted yearly to a greater or lesser extent as a function of proximity to cumulative emissions benchmarks. Adjusting a hard price ceiling yearly using similar criteria would avoid the artificially inflated prices of the soft ceiling while providing for control of cumulative emissions over time. Furthermore, allowing the market to set prices within a controlled price range would provide more information regarding price discovery than Metcalf's variable tax.

4.8 Acknowledgments

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APPENDICES

Appendix A Spatial Optimization for Cellulosic to Ethanol Facilities in Indiana with Sequential Start-ups

The model in Chapter 3 is varied in such a way as to minimize costs over a sequence of ethanol plant start-ups utilizing cellulosic materials. In Chapter 3, costs were minimized for a network of plants in a social planner's context, assuming a simultaneous start-up of the network. By minimizing costs for each plant separately, and assuming a sequential start-up of facilities, the model should simulate more closely how this industry would grow in the real world.

Please recall the model from Chapter 3, restated here for ease of reference: The amount of dry biomass shipped between counties is designated X_{ijk}, where i is the set of counties where biomass is produced, j is the set of counties where ethanol is potentially produced, and k is the set of biomass feedstocks (corn stover and switchgrass). The relevant parameters for the cost minimization model are as follows:

p_k – production cost for biomass feedstock k ($/dry ton shipped with profit)
s_k – fixed shipping cost for biomass feedstock k ($/dry ton shipped)
f – freight rate for shipping biomass ($/dry ton shipped/mile)
d_{ij} – distance from county i to county j (miles)
N – total plant capacity needed (100 Mgal/year)
l – fractional storage loss of biomass feedstock
b_{ik} – amount of biomass k produced in county i (dry tons/yr)
c_k – million gallons of ethanol per dry ton of biomass

The binary {0,1} variables I_j^{50} and I_j^{100} represent the number of 50 million and 100 million gallon ethanol plants respectively in county j, and the model is optimized by minimizing the total cost C as follows:

$$\min_{x_{ijk}, I_j^{50}, I_j^{100}} C = \sum_{i} \sum_{j} \sum_{k} \left(p_k + s_k + fd_{ij} \right) x_{ijk} + \sum_{j} I_j^{50} C^p$$

subject to:

$$\frac{1}{2}\sum_j I_j^{50} + \sum_j I_j^{100} = N \tag{1}$$

$$I_j^{50} + I_j^{100} \leq 1 \text{ for each j} \tag{2}$$

$$\sum_j x_{ijk} \leq (1-l)b_{ik} \text{ for each k and i} \tag{3}$$

$$\sum_i \sum_k c_k x_{ijk} \geq 50 I_j^{50} + 100 I_j^{100} \text{ for each j} \tag{4}$$

$$x_{ijk} \geq 0 \text{ for each i, j, and k} \tag{5}$$

$$I_j^{50} = 0,1 \text{ for each j} \tag{6}$$

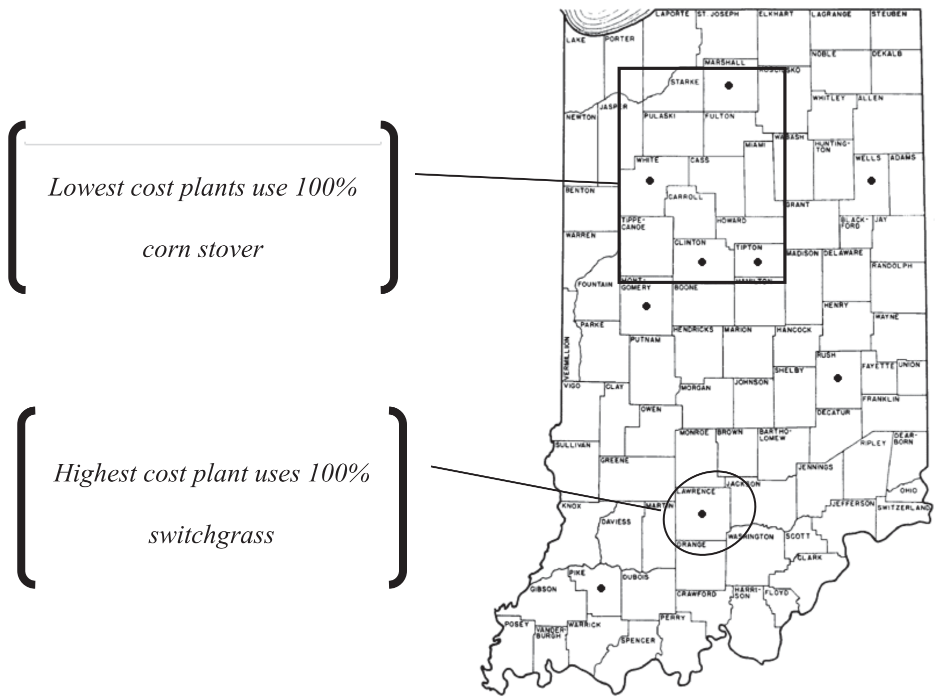
$$I_j^{100} = 0,1 \text{ for each j} \tag{7}$$

The optimization problem has several constraints. Constraints 2, 6, and 7 imply that any county can have at most one plant of either size, 100 Mgal or 50 Mgal, and that fractional plants are not permitted. Constraint 1 requires that the total amount of ethanol produced will exactly exhaust the feedstock resource base. Finally, constraints 3, 4, and 5 require that the amount of biomass supplied by a county cannot exceed the amount available from the farms in that county after taking collection/storage losses into account, and the amount of biomass supplied to each manufacturing site must be sufficient to cover the production level.

The model is revised by minimizing costs over a sequence of plant start-ups ordered by time (t), with costs being described by $\sum_{ijk}(p_k + s_k + f d_{ij})x_{ijkt}$ for each plant (t). Therefore, t is the index for both the ordering of plant start-ups and the specific site that starts up at time t in the ordering. t is indexed from 1 to T, with T being the number of 50 million gallon manufacturing sites required to use most of the biomass available in the state of Indiana (see Appendix B for simulation software). Based on low yield projections, T is equal to 9, resulting in the production of 450 million gallons of cellulosic ethanol per year.

The other significant revision reduces the amount of biomass available to each plant by the amount extracted from previous start-ups. The term for total biomass available, b_{ik}, is therefore replaced by b_{ikt}. This represents the amount of type k cellulosic material available in county i for sequential plant start-up t. For t = 1, b_{ikt} is simply equal to b_{ik} from the social planner's model in Chapter 3. For t > 1, $b_{ikt} = b_{ik(t-1)} - [\sum_j x_{ijk(t-1)}]/(1-l)$.

With these adjustments, the model predicts the network of plants depicted in Figure A.1, with the lowest cost sites starting up first in the corn-rich northwest portion of the state and the highest cost site starting up in the bottom half of the state. These results do not deviate considerably from the results of the social planner model.



●50 Mgal plants

■100 Mgal plants

Figure A.1 Sequential Start-Up of Manufacturing Sites for the Biochemical Conversion of Corn Stover and Switchgrass to Ethanol Based on Low Yield Assumptions and No Economies of Scale.

Table A.1 ranks the sites by cost and reports the percentage of ethanol produced from corn stover for each site. For comparison, the social planner model is run with the assumptions of low yields and 9 sites producing 50 million gallons/yr each. When minimizing costs over the entire network, every site uses some mixture of the two major crops, with low cost sites using mostly corn stover and high cost sites using mostly switchgrass. Utilizing a sequential start-up assumption results in most sites adopting a single, dedicated type of biomass, with lost cost sites using only corn stover and high cost sites using only switchgrass. Therefore, even though the model assumes that plants are able to use any mixture of the 2 biomass types, adopting a sequential start-up framework largely negates this requirement as the manufacturing sites tend to self-segregate.

Table A.1 Cost Ranking and Corn Stover Percentages for Each Plant Site Based on Cost Minimization Procedure: Billion-Ton Assumptions without Economies of Scale

	% Ethanol from Corn Stover	
Low cost ranking*	**Social Planner**	**Sequential Start-up**
1	95%	100%
2	77%	100%
3	69%	100%
4	52%	100%
5	43%	7%
6	36%	9%
7	18%	0%
8	9%	0%
9	17%	0%

* 1 is the lowest cost plant and 9 is the highest cost plant.

In conclusion, having modified the original model in Chapter 3 to accommodate the sequential start-up of profit maximizing plants, the model predicts that the first sites to be constructed will be small in scale (50 million gallons/yr or less), built in high yield corn areas, and utilize 100% corn stover for conversion to ethanol. Only after most of the corn stover has been exhausted will sites begin to utilize switchgrass, and only if ethanol revenues can cover the costs of obtaining such an expensive primary crop.

Appendix B Links to Software Programs

All computer programs can be located at the following site:

http://web.ics.purdue.edu/~perkis/researchsoftware

Links are organized as follows:

Chapter 1 and Appendix A

• Mixed-integer program for plant location model assuming sequential start-ups

Chapter 2

• DM Model with modifications for pretreated recycle

Chapter 3

• Mixed-integer program for plant location model assuming social planner

Chapter 4

• Soft ceiling experimental software

• Reserve auction experimental software

• Baseline experimental software

• Hard ceiling experimental softwar

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Appendix C Subject Instructions for Soft Ceiling Design

Instructions

General

This is an experiment in the economics of decision making. The instructions are simple and if you follow them carefully and make good decisions you will earn money that will be paid to you privately in cash. All earnings on your computer screens are in Experimental Dollars. These Experimental Dollars will be converted to real Dollars at the end of the experiment, at a rate of __200__ Experimental Dollars = 1 real Dollar. Notice that the more Experimental Dollars that you earn, the more cash that you receive at the end of the experiment.

We are going to conduct a number of periods. Attached to these instructions you will find a sheet labeled Personal Record Sheet, which will help you keep track of how your decisions impact your earnings. You are not to reveal this information to anyone. It is your own private information.

Each period you will produce units of a good. For every unit of the good that you produce, you will incur a production cost which will take away from your earnings. In order to avoid these costs, you may wish to purchase "coupons." Each coupon allows you to produce 1 less unit of the good.

At the beginning of each period you will receive cash in the form of a Fixed Period Revenue. There will then be two coupon trading stages during which time you may purchase or sell coupons with other participants. (Each of you will receive coupons before one or both trading stages so that you have something to trade.) At the end of each period you will pay your production costs. Your earnings each period are determined as follows:

Earnings = Fixed Period Revenue – Total Production Costs
+ Sale Proceeds from Selling Coupons – Amount Spent when Buying Coupons.

Your Fixed Period Revenue does not depend on any actions you take, and does not change throughout the experiment. (In fact, it is already written on your Personal Record Sheet.) You will receive this revenue at the beginning of each period so that you have cash available with which to trade.

Production Costs

You must pay production costs when you produce units. The cost of each unit produced is typically different from the cost of other units produced, and your costs may or may not be different from the costs of other participants. Your production costs are always shown on the left side of your computer screen, as illustrated in Figure 1 (the numbers on this example screen are different from the actual numbers used in the experiment, and you won't actually learn your values until the experiment begins). Everyone can produce up to 10 units, and the cost of each unit is written separately.

For example, based on the numbers shown in the *example* in Figure 1, your first unit produced would cost 100, your second unit produced would cost 200, etc. If, for example, these were your production costs and you produced 3 units, your **total** costs would be 100+200+300=600. So you must recognize that the costs shown on your screen are the **extra** costs associated with each **additional** unit produced.

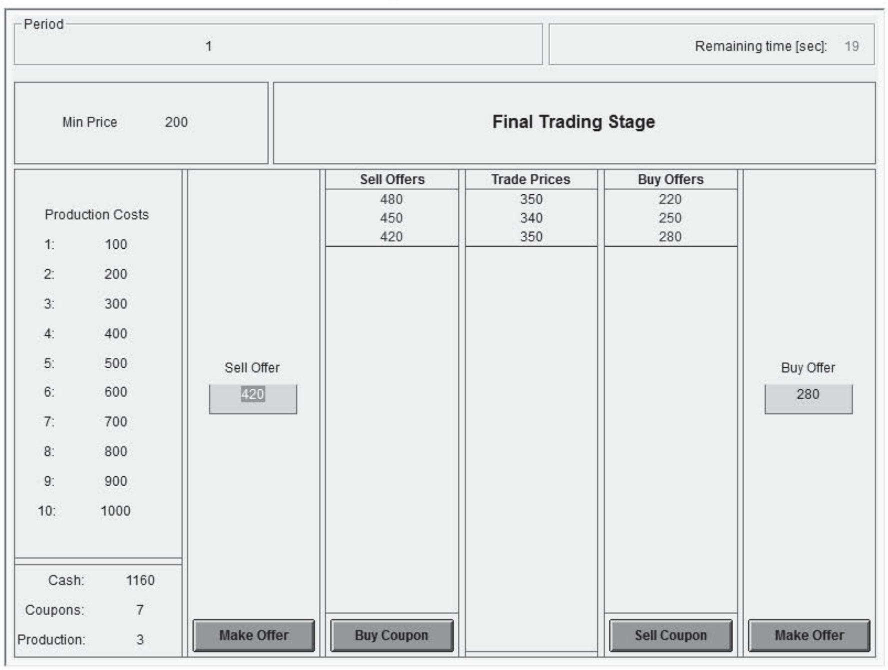

Figure 1

Coupons

We've already explained that your Fixed Period Revenue never changes, but your costs increase when you increase production. So why should you ever produce any units? The reason comes from today's compliance rule:

Compliance Rule: The sum of your production amount + coupons must equal 10

This rule means that you can avoid production (and save on your production costs) by holding coupons. Anyone can adjust their own holding of coupons by buying and selling them in a market that will operate over the computer network. If you sell coupons your cash increases by the sale amount, and if you buy coupons your cash decreases by the sale amount. Later in these instructions we explain the rules for buying and selling coupons.

Why might you want to buy a coupon? <u>Remember that coupons allow you to avoid production, and they are always applied to the most expensive production first</u>. If you currently hold 7 coupons, for example, and if you had the example production costs shown in Figure 1, then the last unit that you are supposed to produce is the 3rd unit (so that your production of 3 + coupons of 7 = 10). The production cost of this 3rd unit is 300. So if you can buy a coupon for less than 300, this might be a good idea since it allows you to save the production cost of 300. For example, if you bought one additional coupon for 280, you save the production cost of 300 and therefore make a profit (because of the lower costs that you need to incur) of 300-280=20.

Why might you want to sell a coupon? Continuing the illustration based on the example production costs shown in Figure 1, suppose that you currently still hold 7 coupons and the cost of the last unit produced is still 300. If you had 1 less coupon, the cost of the next unit produced (the 4th unit) would be 400. If you can sell a coupon for more than 400, this might be a good idea since these sales revenues exceed the production costs of this 4th unit. For example, if you sell a coupon for 420, even if you incur the additional (4th unit) production cost of 400 you would still make a profit on this sale of 420-400=20.

Coupon Trading Stage: How to Buy and Sell Coupons

During the trading stage, coupons can be purchased from and sold to other participants. At any time during the trading stage, everyone is free to make an offer to buy a coupon at a price they choose; likewise, everyone is free to make an offer to sell a coupon at a price they choose. Also at any time during the period, everyone is free to buy at the best offer price specified by someone wishing to sell, and everyone is free to sell at the best offer price specified by someone wishing to buy. (Of course, there are some limits: to sell a unit or make a sales offer, you need to have a coupon to sell. And to buy a unit or make a buy offer, you need to have enough cash to pay.)

You will enter offer prices and accept prices to execute transactions using your computer. Figure 1 (displayed again on a separate sheet for your convenience) shows the market trading screen for one of the coupon trading stages. The time left in the period is shown on the upper right of the trading screen. You will have 2 minutes to buy and/or sell coupons in each trading stage.

Buying coupons

Participants interested in buying can submit offer prices using the "Buy Offer" box in the right side of the screen, and then clicking on the "Make Offer" button in the lower right. This offer price is immediately displayed on all traders' computers on the upper right part of the screen, labelled "Buy Offers." Once this offer price has been submitted, it is binding in the sense that anyone wishing to sell can accept this price offer. Such an acceptance results in an immediate trade at that price. The previous trading prices in the current period are displayed in the "Trading Prices" list in the center of your computer screen.

If there are already Buy Offers displayed in the current period, then new buy offers submitted by anyone wishing to buy must provide better trading terms to the sellers. Sellers prefer higher prices, so any new buy offers must be higher than the current highest buy offer. Your computer will give you an error message if you try to offer a lower price than the best price currently available.

Another way to buy coupons is with the "Buy Coupon" button. Anyone wishing to buy can accept the best (that is, lowest) sell offer price by simply clicking the "Buy Coupon" button on the bottom of their computer screen. This results in an immediate trade at that price.

Regardless of how you buy coupons, your coupon and cash totals will be updated at the time of purchase. You can always find these totals in the bottom left of the screen, along with your production level if you maintain your current level of coupons.

Selling Coupons

Participants interested in selling can submit offer prices using the “Sell Offer” box on the left side of the screen, and then clicking on the “Make Offer” button below this box. This offer price is immediately displayed on all traders’ computers on the left part of the screen, labelled “Sell Offers.” Once this offer price has been submitted, it is binding in the sense that anyone wishing to buy can accept this price offer. Such an acceptance results in an immediate trade at that price.

If there are already Sell Offers displayed in the current period, then new sell offers submitted by anyone wishing to sell must provide better trading terms to the buyers. Buyers prefer lower prices, so any new sell offers must be lower than the current lowest sell offer. Your computer will give you an error message if you try to offer a higher price than the best price currently available.

Another way to sell coupons is with the “Sell Coupon” button. Anyone wishing to sell can accept the best (that is, highest offer price) by simply clicking the “Sell Coupon” button on the bottom of their computer screen. This results in an immediate trade at that price.

Regardless of how you sell coupons, your coupon and cash totals will be updated at the time of sale. You can always find these totals in the bottom left of the screen, along with your production level if you maintain your current level of coupons.

Period Structure

This experiment will consist of 2 practice periods followed by 12 paid periods. Each period is identical and will include the following steps in Figure 2:

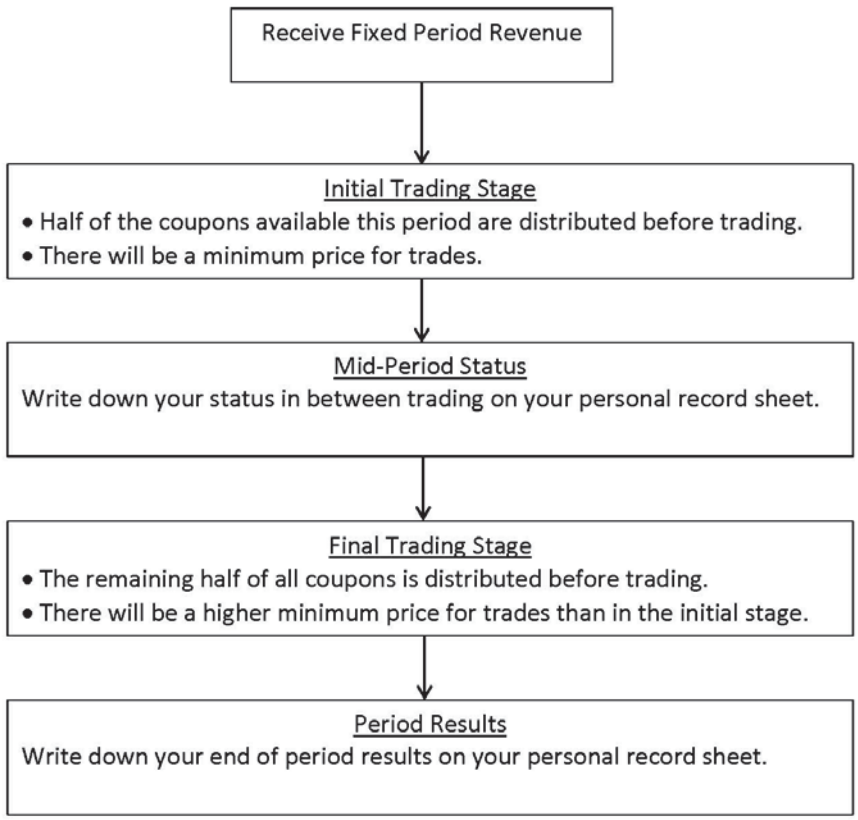

Figure 2

Initial Trading Stage and Minimum Prices

During each period, you will have two separate trading stages during which you may choose to buy and/or sell coupons, an "Initial Trading Stage" and a "Final Trading Stage," each lasting 2 minutes. Each trading stage will also have a "Min Price," which is the minimum or lowest price at which a coupon can be purchased or sold. During the Initial Trading Stage, the Min Price and the Min Price Next Stage are listed in the top left corner of the screen (Figure 3).

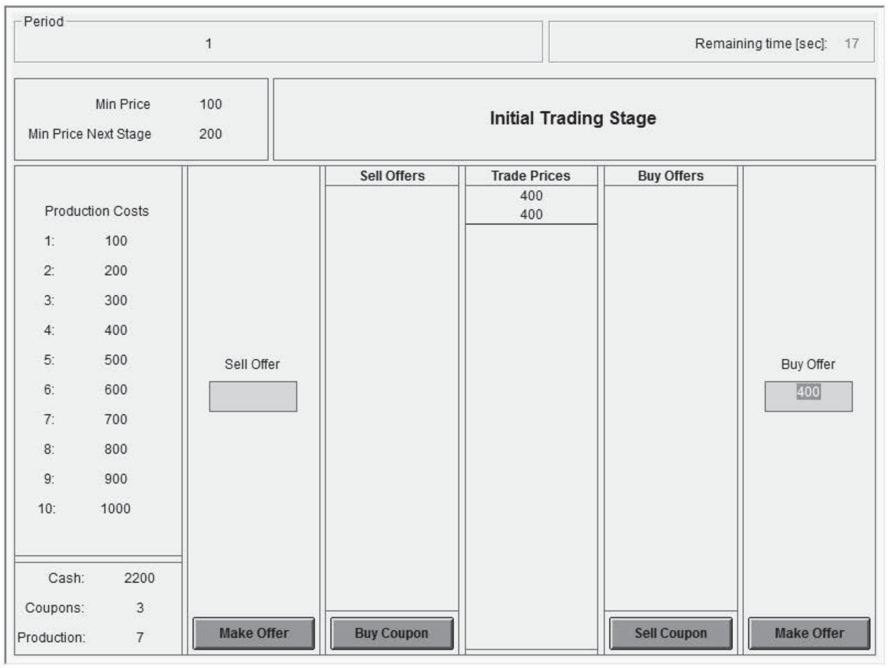

Figure 3

In the example in Figure 3, you would be trading in the Initial Trading Stage with a minimum price of 100, knowing that the minimum price in the Final Trading Stage will be 200. Suppose you wished to purchase a coupon for 150. You would only be able to make this trade in the Initial Trading Stage since the minimum price during final trading would be higher than 150.

Mid-Period Status and Coupon Distribution

Each period, coupons will be distributed to participants at the beginning of both trading stages. Half of all coupons will be distributed amongst participants before the Initial Trading Stage, with the remaining half distributed before the Final Trading Stage. (Your personal coupon amounts are already on your record sheet.) The Mid-Period Status screen (Figure 4) will provide you with a summary of your coupon levels. You will enter this on your record sheet.

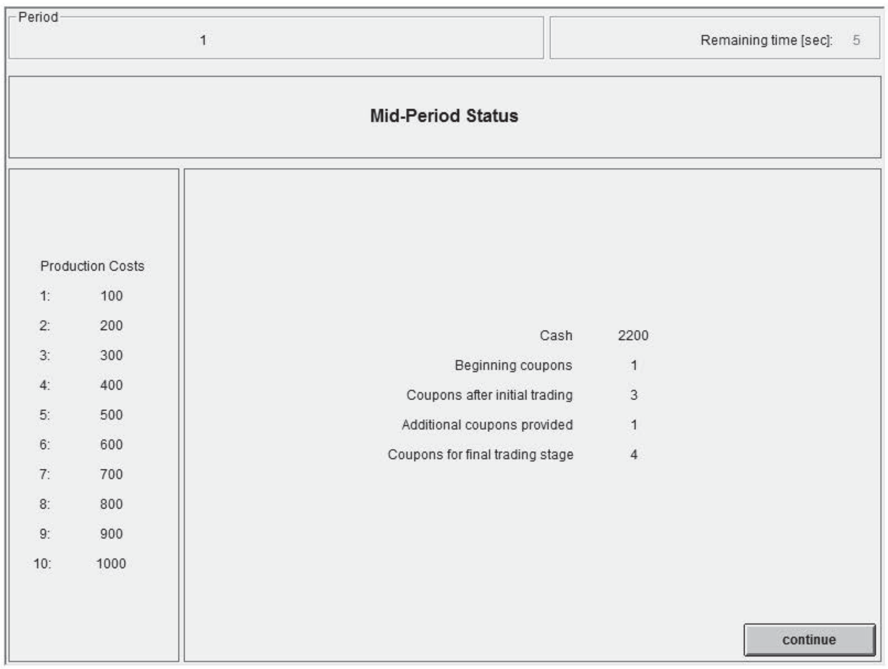

Figure 4

In this example, you started the Initial Trading Stage with 1 coupon and held 3 coupons after initial trading was complete. You receive 1 additional coupon, bringing your total coupons to 4 for the start of the Final Trading Stage.

Once you have recorded the Mid-Period Status information, you can hit the continue button.

Final Trading Stage

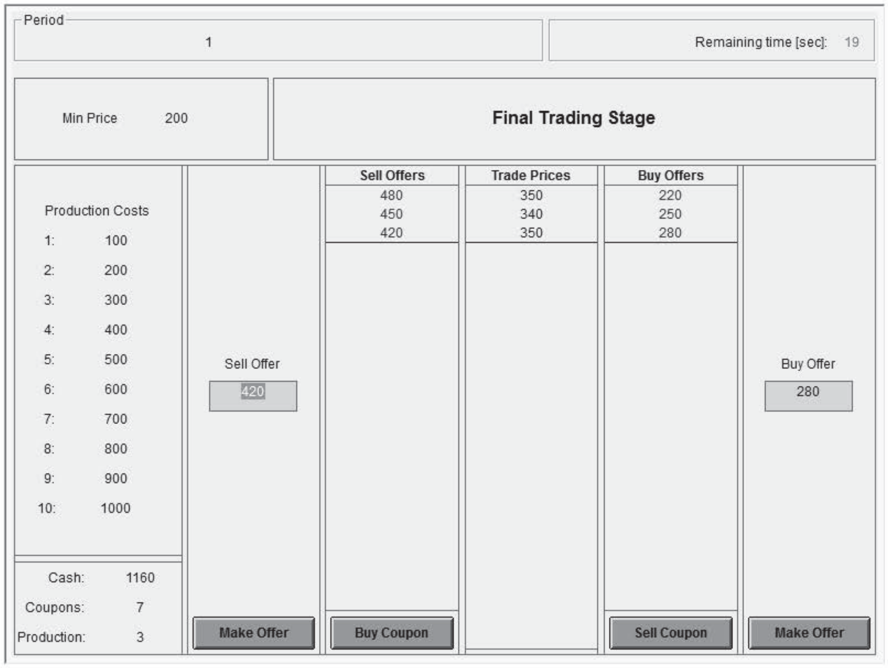

Figure 1 (repeat)

The Final Trading Stage screen is similar to the other trading screen. Note that the Min Price in this example is 200, as you were told it would be from the previous trading stage. This confirms that the lowest price at which a trade can now be made is 200. Any offers made below 200 would be rejected.

Period Results

Once trading has been completed, the results of the period will display on the screen. You should copy this information onto your Personal Record Sheet at the end of each period, and then click "continue" to begin the next period.

Figure 2 provides an example of the information provided in the period results. In this example, you have accumulated 7 coupons and are therefore required to produce 3 units of the good based on the compliance rule (7 coupons + 3 units produced = 10). Your actual production level is determined automatically by the computer using this compliance rule.

Since you produced 3 units of the good, your total production costs are the sum of the costs for each of the first three units (100 + 200 + 300 = 600). Note that your production costs are still listed on this page in order to help you assess your strategies for buying and selling coupons during the trading stages. Lastly, your period and total profits are provided.

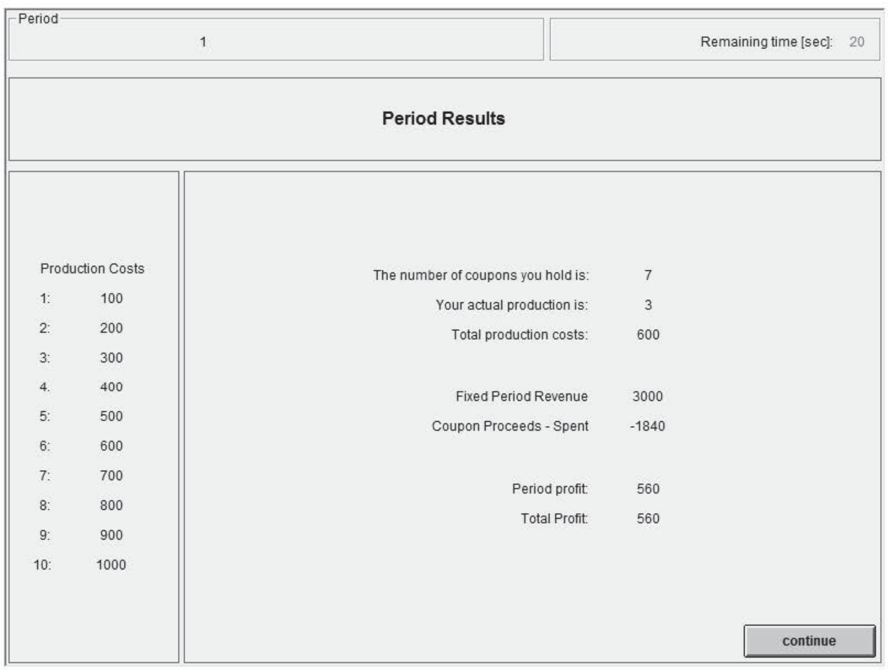

Figure 5

Summary

- Your production costs shown on the left of your computer screen are the extra, additional costs incurred for each unit that you produce.
- To be in compliance, your coupons + units produced = 10.
- There will be 2 trading stages. During either trading stage, coupons can be purchased or sold by anyone at any price above the Min Price listed on the screen. The Min Price will be higher for the Final Trading Stage.
- Half of all coupons will be distributed before initial trading with the remaining half distributed before final trading. You might be provided with coupons at the beginning of either trading stage during each period.
- Your current cash and coupon holdings, as well as the corresponding production level, are always provided during trading on the bottom left of your computer screen.
- Your coupon receipts and changes in coupon levels will be provided during the Mid-Period Results stage in between the 2 trading stages.
- Your coupon holdings, actual production level, and period profits will be provided during the Period Results stage at the end of each period. No coupons or cash will be carried over into the next period for use in trading.

Please note that while you cannot purchase coupons if you do not hold enough cash, you can have a negative profit for a period if your production costs are greater than your available cash after trading. Once we begin the experiment you should be careful to maintain positive cash holdings, since anyone whose period profit is below zero for 3 consecutive periods will be considered bankrupt and will no longer be allowed to participate in the experiment.

If you have any questions during the experiment, please raise your hand and I will come to your terminal. Are there any questions now before we begin the experiment?

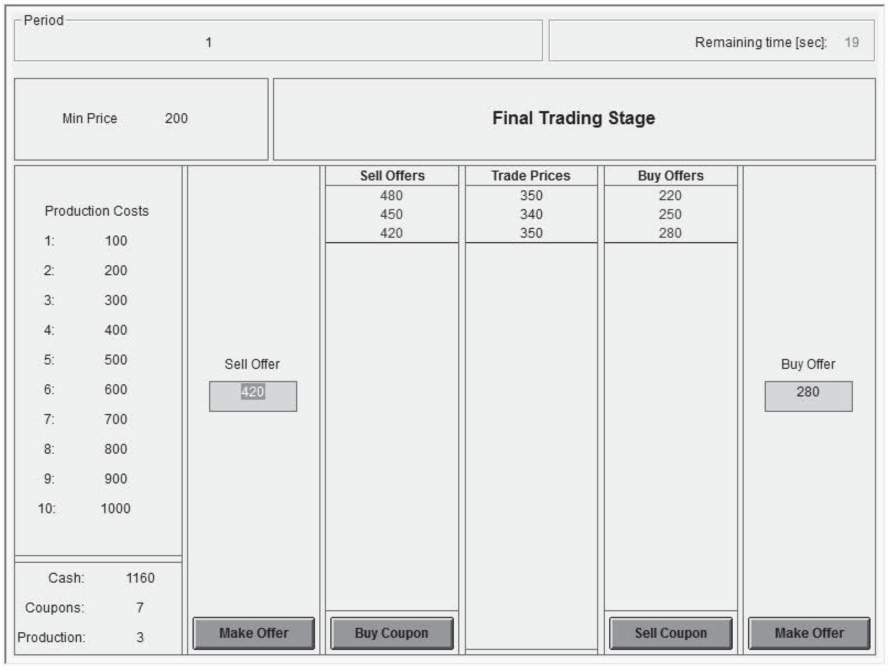
Period
1
Remaining time [sec]: 19
Min Price 200
Final Trading Stage
Production Costs
1: 100
2: 200
3: 300
4: 400
5: 500
6: 600
7: 700
8: 800
9: 900
10: 1000
Cash: 1160
Coupons: 7
Production: 3
Sell Offer
420
Make Offer
Sell Offers
480
450
420
Buy Coupon
Trade Prices
350
340
350
Buy Offers
220
250
280
Sell Coupon
Buy Offer
280
Make Offer

Figure 1

Personal Record Sheet for Subject ID __________

	Mid-Period Status					Period Results						
Period	**Cash**	**Initial Coupons**	**Coupons After Initial Trading**	**Added Coupons**	**Coupons for Final Trading**	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1		1		0					1220			Practice
2		1		0					1220			Practice
1		1		0					1220			
2		1		0					1220			
3		1		0					1220			
4		1		0					1220			
5		1		0					1220			
6		1		0					1220			
7		1		0					1220			
8		1		0					1220			
9		1		0					1220			
10		1		0					1220			
11		1		0					1220			
12		1		0					1220			
									Conversion Rate →	Total Profits / 200	Converted Total →	

Personal Record Sheet for Subject ID _________

	Mid-Period Status					Period Results						
Period	**Cash**	**Initial Coupons**	**Coupons After Initial Trading**	**Added Coupons**	**Coupons for Final Trading**	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1		0		1					1160			Practice
2		0		1					1160			Practice
1		0		1					1160			
2		0		1					1160			
3		0		1					1160			
4		0		1					1160			
5		0		1					1160			
6		0		1					1160			
7		0		1					1160			
8		0		1					1160			
9		0		1					1160			
10		0		1					1160			
11		0		1					1160			
12		0		1					1160			
									Conversion Rate →	Total Profits / 200	Converted Total →	

Personal Record Sheet for Subject ID ________

	Mid-Period Status					Period Results							
Period	**Cash**	**Initial Coupons**	**Coupons After Initial Trading**	**Added Coupons**	**Coupons for Final Trading**	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1		1		0					1150			Practice
2		1		0					1150			Practice
1		1		0					1150			
2		1		0					1150			
3		1		0					1150			
4		1		0					1150			
5		1		0					1150			
6		1		0					1150			
7		1		0					1150			
8		1		0					1150			
9		1		0					1150			
10		1		0					1150			
11		1		0					1150			
12		1		0					1150			
									Conversion Rate →	Total Profits / 200	Converted Total →	

Personal Record Sheet for Subject ID ________

	Mid-Period Status					Period Results						
Period	Cash	Initial Coupons	Coupons After Initial Trading	Added Coupons	Coupons for Final Trading	Coupons Held (End of Period)	Actual Production	Total Production Costs	Fixed Period Revenue	Coupon Proceeds - Spent	Period Profits	Total Profits
1		0		1					1120			Practice
2		0		1					1120			Practice
1		0		1					1120			
2		0		1					1120			
3		0		1					1120			
4		0		1					1120			
5		0		1					1120			
6		0		1					1120			
7		0		1					1120			
8		0		1					1120			
9		0		1					1120			
10		0		1					1120			
11		0		1					1120			
12		0		1					1120			
									Conversion Rate →	Total Profits / 200	Converted Total →	

Personal Record Sheet for Subject ID ________

	Mid-Period Status					Period Results							
Period	**Cash**	**Initial Coupons**	**Coupons After Initial Trading**	**Added Coupons**	**Coupons for Final Trading**	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1		5		4					240			Practice
2		5		4					240			Practice
1		5		4					240			
2		5		4					240			
3		5		4					240			
4		5		4					240			
5		5		4					240			
6		5		4					240			
7		5		4					240			
8		5		4					240			
9		5		4					240			
10		5		4					240			
11		5		4					240			
12		5		4					240			
									Conversion Rate →	Total Profits / 200	Converted Total →	

Personal Record Sheet for Subject ID _________

	Mid-Period Status					Period Results						
Period	**Cash**	**Initial Coupons**	**Coupons After Initial Trading**	**Added Coupons**	**Coupons for Final Trading**	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1		5		4					220			Practice
2		5		4					220			Practice
1		5		4					220			
2		5		4					220			
3		5		4					220			
4		5		4					220			
5		5		4					220			
6		5		4					220			
7		5		4					220			
8		5		4					220			
9		5		4					220			
10		5		4					220			
11		5		4					220			
12		5		4					220			
									Conversion Rate →	Total Profits / 200	Converted Total →	

Personal Record Sheet for Subject ID ________

	Mid-Period Status					Period Results						
Period	Cash	Initial Coupons	Coupons After Initial Trading	Added Coupons	Coupons for Final Trading	Coupons Held (End of Period)	Actual Production	Total Production Costs	Fixed Period Revenue	Coupon Proceeds - Spent	Period Profits	Total Profits
1		4		5					150			Practice
2		4		5					150			Practice
1		4		5					150			
2		4		5					150			
3		4		5					150			
4		4		5					150			
5		4		5					150			
6		4		5					150			
7		4		5					150			
8		4		5					150			
9		4		5					150			
10		4		5					150			
11		4		5					150			
12		4		5					150			
									Conversion Rate →	Total Profits / 200	Converted Total →	

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Personal Record Sheet for Subject ID ________

	Mid-Period Status					Period Results						
Period	Cash	Initial Coupons	Coupons After Initial Trading	Added Coupons	Coupons for Final Trading	Coupons Held (End of Period)	Actual Production	Total Production Costs	Fixed Period Revenue	Coupon Proceeds - Spent	Period Profits	Total Profits
1		4		5					190			Practice
2		4		5					190			Practice
1		4		5					190			
2		4		5					190			
3		4		5					190			
4		4		5					190			
5		4		5					190			
6		4		5					190			
7		4		5					190			
8		4		5					190			
9		4		5					190			
10		4		5					190			
11		4		5					190			
12		4		5					190			
									Conversion Rate →	Total Profits / 200	Converted Total →	

Appendix D Subject Instructions for Reserve Auction Design

Instructions

General

This is an experiment in the economics of decision making. The instructions are simple and if you follow them carefully and make good decisions you will earn money that will be paid to you privately in cash. All earnings on your computer screens are in Experimental Dollars. These Experimental Dollars will be converted to real Dollars at the end of the experiment, at a rate of _200__ Experimental Dollars = 1 real Dollar. Notice that the more Experimental Dollars that you earn, the more cash that you receive at the end of the experiment.

We are going to conduct a number of periods. Attached to these instructions you will find a sheet labeled Personal Record Sheet, which will help you keep track of how your decisions impact your earnings. You are not to reveal this information to anyone. It is your own private information.

Each period you will produce units of a good. For every unit of the good that you produce, you will incur a production cost which will take away from your earnings. In order to avoid these costs, you may wish to purchase "coupons." Each coupon allows you to produce 1 less unit of the good.

At the beginning of each period you will receive cash in the form of a Fixed Period Revenue. There will then be two coupon trading stages during which time you may purchase or sell coupons with other participants. (Each of you will receive coupons before one or both trading stages so that you have something to trade.) At the end of each period you will pay your production costs. Your earnings each period are determined as follows:

Earnings = Fixed Period Revenue – Total Production Costs
+ Sale Proceeds from Selling Coupons – Amount Spent when Buying Coupons.

Your Fixed Period Revenue does not depend on any actions you take, and does not change throughout the experiment. (In fact, it is already written on your Personal Record Sheet.) You will receive this revenue at the beginning of each period so that you have cash available with which to trade.

Production Costs

You must pay production costs when you produce units. The cost of each unit produced is typically different from the cost of other units produced, and your costs may or may not be different from the costs of other participants. Your production costs are always shown on the left side of your computer screen, as illustrated in Figure 1 (the numbers on this example screen are different from the actual numbers used in the experiment, and you won't actually learn your values until the experiment begins). Everyone can produce up to 10 units, and the cost of each unit is written separately.

For example, based on the numbers shown in the *example* in Figure 1, your first unit produced would cost 100, your second unit produced would cost 200, etc. If, for example, these were your production costs and you produced 3 units, your **total** costs would be 100+200+300=600. So you must recognize that the costs shown on your screen are the **extra** costs associated with each **additional** unit produced.

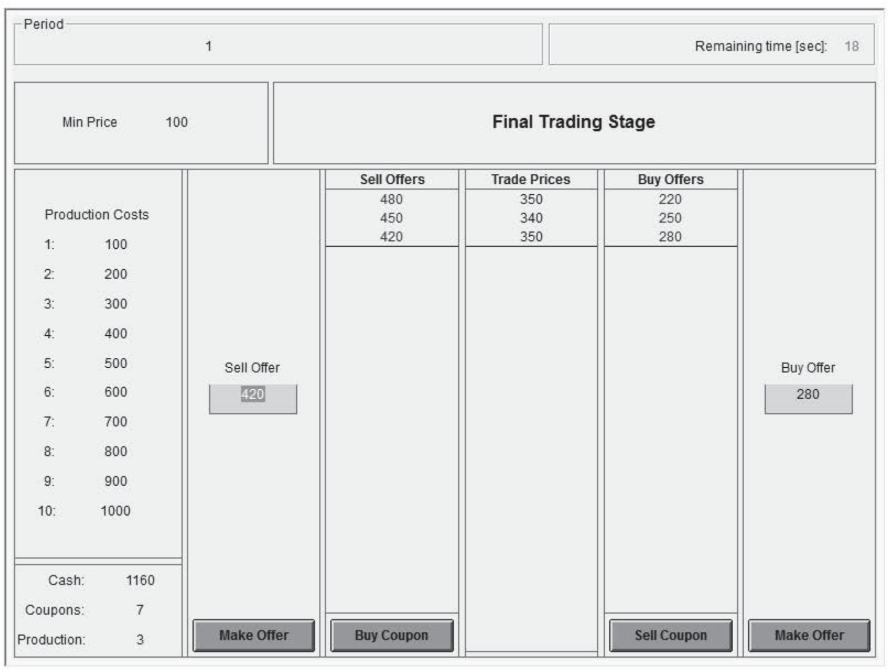


Figure 1

Coupons

We've already explained that your Fixed Period Revenue never changes, but your costs increase when you increase production. So why should you ever produce any units? The reason comes from today's compliance rule:

Compliance Rule: The sum of your production amount + coupons must equal 10

This rule means that you can avoid production (and save on your production costs) by holding coupons. Anyone can adjust their own holding of coupons by buying and selling them in a market that will operate over the computer network. If you sell coupons your cash increases by the sale amount, and if you buy coupons your cash decreases by the sale amount. Later in these instructions we explain the rules for buying and selling coupons.

Why might you want to buy a coupon? Remember that coupons allow you to avoid production, and they are always applied to the most expensive production first. If you currently hold 7 coupons, for example, and if you had the example production costs shown in Figure 1, then the last unit that you are supposed to produce is the 3rd unit (so that your production of 3 + coupons of 7 = 10). The production cost of this 3rd unit is 300. So if you can buy a coupon for less than 300, this might be a good idea since it allows you to save the production cost of 300. For example, if you bought one additional coupon for 280, you save the production cost of 300 and therefore make a profit (because of the lower costs that you need to incur) of 300-280=20.

Why might you want to sell a coupon? Continuing the illustration based on the example production costs shown in Figure 1, suppose that you currently still hold 7 coupons and the cost of the last unit produced is still 300. If you had 1 less coupon, the cost of the next unit produced (the 4th unit) would be 400. If you can sell a coupon for more than 400, this might be a good idea since these sales revenues exceed the production costs of this 4th unit. For example, if you sell a coupon for 420, even if you incur the additional (4th unit) production cost of 400 you would still make a profit on this sale of 420-400=20.

Coupon Trading Stage: How to Buy and Sell Coupons

During the trading stage, coupons can be purchased from and sold to other participants. At any time during the trading stage, everyone is free to make an offer to buy a coupon at a price they choose; likewise, everyone is free to make an offer to sell a coupon at a price they choose. Also at any time during the period, everyone is free to buy at the best offer price specified by someone wishing to sell, and everyone is free to sell at the best offer price specified by someone wishing to buy. (Of course, there are some limits: to sell a unit or make a sales offer, you need to have a coupon to sell. And to buy a unit or make a buy offer, you need to have enough cash to pay.)

You will enter offer prices and accept prices to execute transactions using your computer. Figure 1 (displayed again on a separate sheet for your convenience) shows the market trading screen for one of the coupon trading stages. The time left in the period is shown on the upper right of the trading screen. You will have 2 minutes to buy and/or sell coupons in each trading stage.

Buying coupons

Participants interested in buying can submit offer prices using the "Buy Offer" box in the right side of the screen, and then clicking on the "Make Offer" button in the lower right. This offer price is immediately displayed on all traders' computers on the upper right part of the screen, labelled "Buy Offers." Once this offer price has been submitted, it is binding in the sense that anyone wishing to sell can accept this price offer. Such an acceptance results in an immediate trade at that price. The previous trading prices in the current period are displayed in the "Trading Prices" list in the center of your computer screen.

If there are already Buy Offers displayed in the current period, then new buy offers submitted by anyone wishing to buy must provide better trading terms to the sellers. Sellers prefer higher prices, so any new buy offers must be higher than the current highest buy offer. Your computer will give you an error message if you try to offer a lower price than the best price currently available.

Another way to buy coupons is with the "Buy Coupon" button. Anyone wishing to buy can accept the best (that is, lowest) sell offer price by simply clicking the "Buy Coupon" button on the bottom of their computer screen. This results in an immediate trade at that price.

Regardless of how you buy coupons, your coupon and cash totals will be updated at the time of purchase. You can always find these totals in the bottom left of the screen, along with your production level if you maintain your current level of coupons.

Selling Coupons

Participants interested in selling can submit offer prices using the "Sell Offer" box on the left side of the screen, and then clicking on the "Make Offer" button below this box. This offer price is immediately displayed on all traders' computers on the left part of the screen, labelled "Sell Offers." Once this offer price has been submitted, it is binding in the sense that anyone wishing to buy can accept this price offer. Such an acceptance results in an immediate trade at that price.

If there are already Sell Offers displayed in the current period, then new sell offers submitted by anyone wishing to sell must provide better trading terms to the buyers. Buyers prefer lower prices, so any new sell offers must be lower than the current lowest sell offer. Your computer will give you an error message if you try to offer a higher price than the best price currently available.

Another way to sell coupons is with the "Sell Coupon" button. Anyone wishing to sell can accept the best (that is, highest offer price) by simply clicking the "Sell Coupon" button on the bottom of their computer screen. This results in an immediate trade at that price.

Regardless of how you sell coupons, your coupon and cash totals will be updated at the time of sale. You can always find these totals in the bottom left of the screen, along with your production level if you maintain your current level of coupons.

Period Structure

This experiment will consist of 2 practice periods followed by 12 paid periods. Each period is identical and will include the following steps in Figure 2:

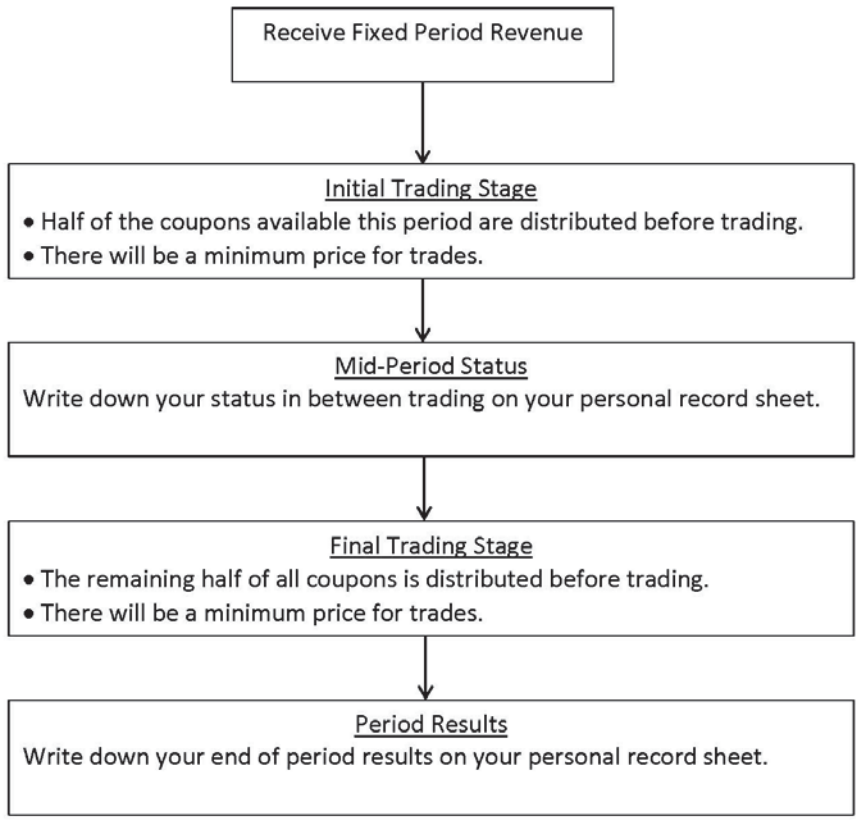


Figure 2

Initial Trading Stage

During each period, you will have two separate trading stages during which you may choose to buy and/or sell coupons, an "Initial Trading Stage" and a "Final Trading Stage," each lasting 2 minutes. Each trading stage will also have a "Min Price," which is the minimum or lowest price at which a coupon can be purchased or sold. During the Initial Trading Stage, the Min Price and the Min Price Next Stage are listed in the top left corner of the screen (Figure 3).

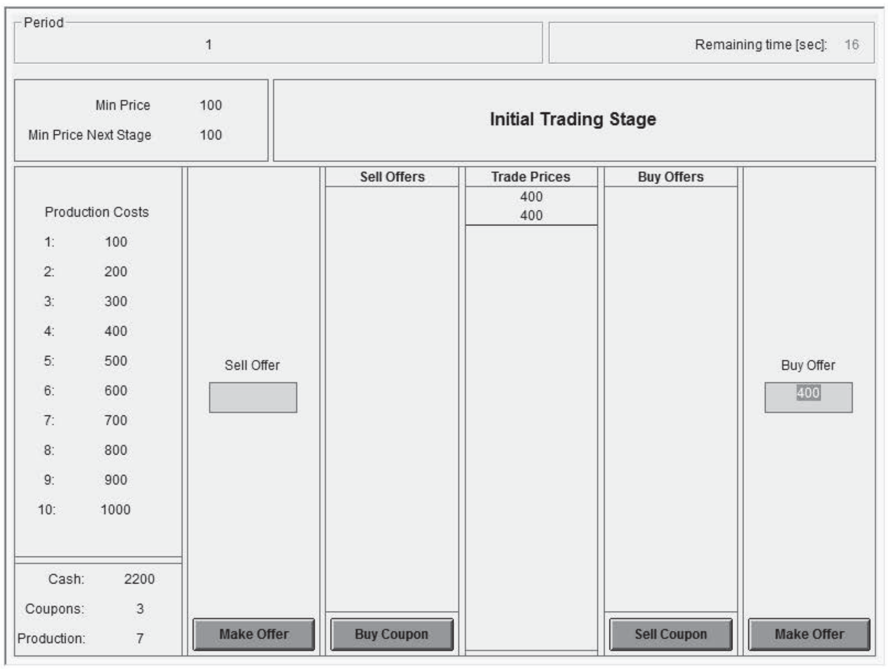


Figure 3

In the example in Figure 3, you would be trading in the Initial Trading Stage with a minimum price of 100, knowing that the minimum price in the Final Trading Stage will also be 100.

Mid-Period Status

Each period, coupons will be distributed to participants at the beginning of both trading stages. Half of all coupons will be distributed amongst participants before the Initial Trading Stage, with the remaining half distributed before the Final Trading Stage. (Your personal coupon amounts are already on your record sheet.) The Mid-Period Status screen (Figure 4) will provide you with a summary of your coupon levels. You will enter this on your record sheet.

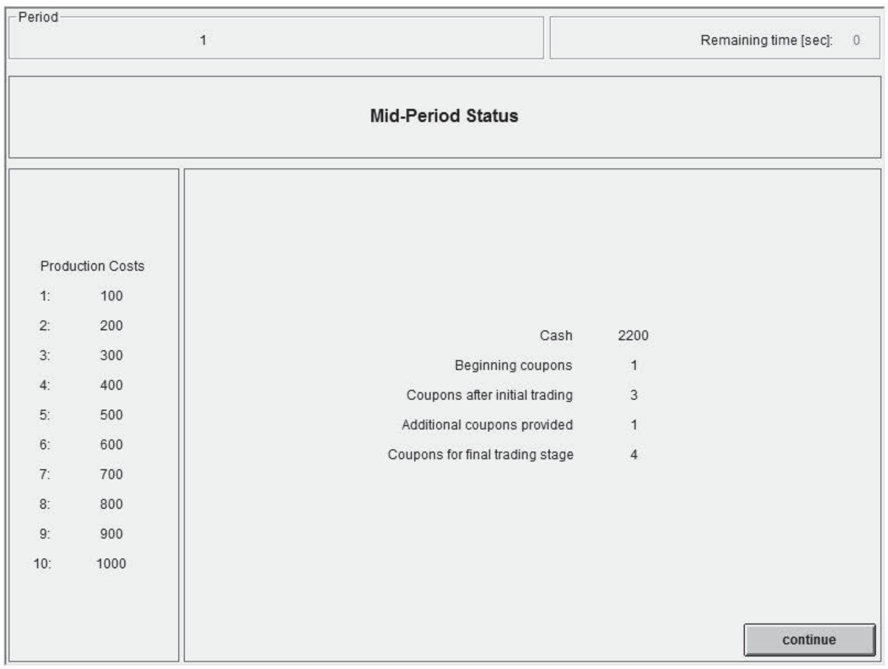


Figure 4

In this example, you started the Initial Trading Stage with 1 coupon and held 3 coupons after initial trading was complete. You receive 1 additional coupon, bringing your total coupons to 4 for the start of the Final Trading Stage.

Once you have recorded the Mid-Period Status information, you can hit the continue button.

Final Trading Stage

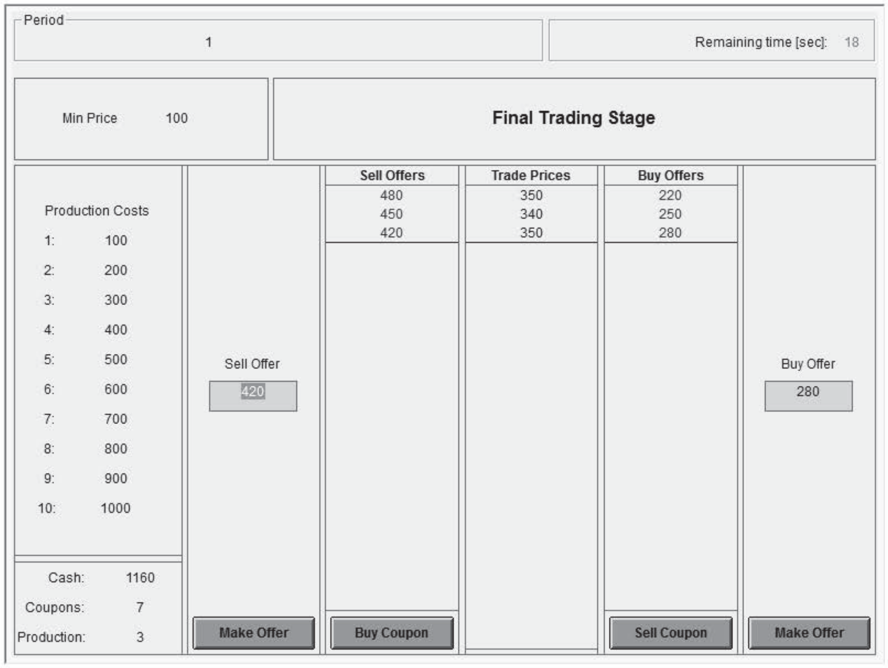


Figure 1 (repeat)

The Final Trading Stage screen is similar to the other trading screen. Note that the Min Price in this example is 100, as you were told it would be from the previous trading stage. Any offers made below 100 would be rejected.

Period Results

Once trading has been completed, the results of the period will display on the screen. You should copy this information onto your Personal Record Sheet at the end of each period, and then click "continue" to begin the next period.

Figure 2 provides an example of the information provided in the period results. In this example, you have accumulated 7 coupons and are therefore required to produce 3 units of the good based on the compliance rule (7 coupons + 3 units produced = 10). Your actual production level is determined automatically by the computer using this compliance rule.

Since you produced 3 units of the good, your total production costs are the sum of the costs for each of the first three units (100 + 200 + 300 = 600). Note that your production costs are still listed on this page in order to help you assess your strategies for buying and selling coupons during the trading stages. Lastly, your period and total profits are provided.

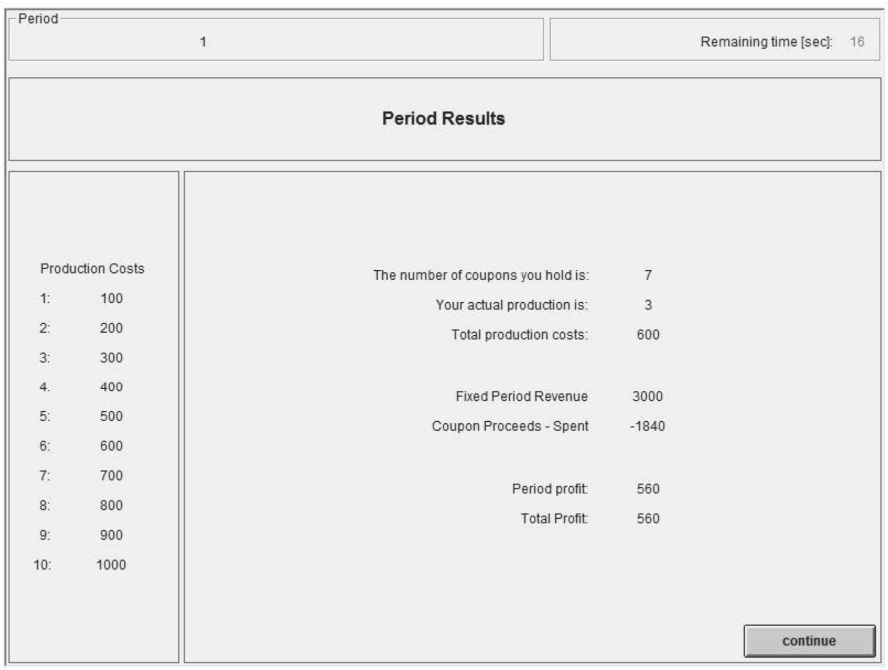


Figure 5

Summary

- Your production costs shown on the left of your computer screen are the extra, additional costs incurred for each unit that you produce.
- To be in compliance, your coupons + units produced = 10.
- There will be 2 trading stages. During either trading stage, coupons can be purchased or sold by anyone at any price above the Min Price listed on the screen.
- Half of all coupons will be distributed before initial trading with the remaining half distributed before final trading. You might be provided with coupons at the beginning of either trading stage during each period.
- Your current cash and coupon holdings, as well as the corresponding production level, are always provided during trading on the bottom left of your computer screen.
- Your coupon receipts and changes in coupon levels will be provided during the Mid-Period Results stage in between the 2 trading stages.
- Your coupon holdings, actual production level, and period profits will be provided during the Period Results stage at the end of each period. No coupons or cash will be carried over into the next period for use in trading.

Please note that while you cannot purchase coupons if you do not hold enough cash, you can have a negative profit for a period if your production costs are greater than your available cash after trading. Once we begin the experiment you should be careful to maintain positive cash holdings, since anyone whose period profit is below zero for 3 consecutive periods will be considered bankrupt and will no longer be allowed to participate in the experiment.

If you have any questions during the experiment, please raise your hand and I will come to your terminal. Are there any questions now before we begin the experiment?

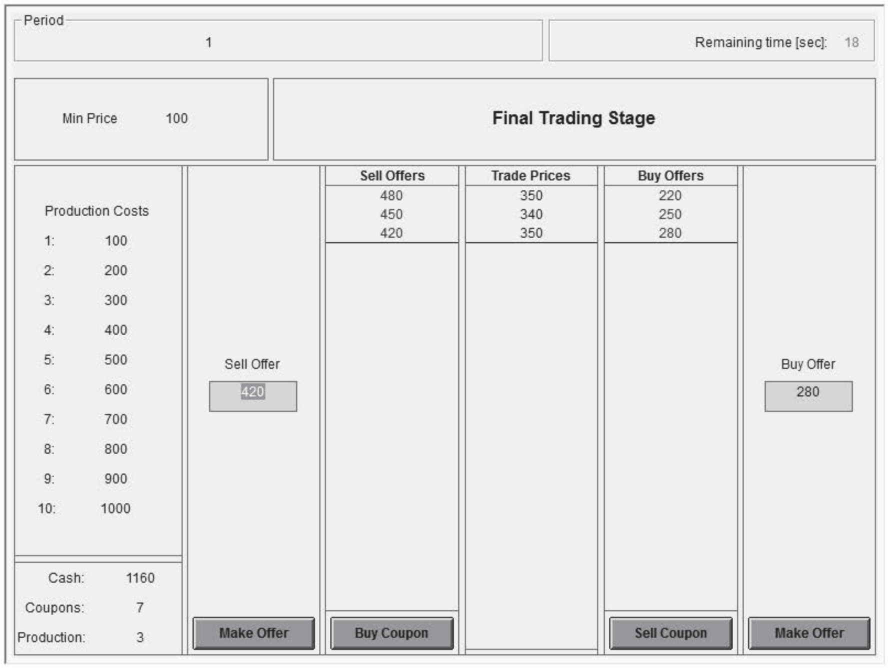

Period
1
Remaining time [sec]: 18
Min Price 100
Final Trading Stage
Production Costs
1: 100
2: 200
3: 300
4: 400
5: 500
6: 600
7: 700
8: 800
9: 900
10: 1000
Cash: 1160
Coupons: 7
Production: 3
Sell Offer
420
Make Offer
Sell Offers
480
450
420
Buy Coupon
Trade Prices
350
340
350
Buy Offers
220
250
280
Sell Coupon
Buy Offer
280
Make Offer

Figure 1

Personal Record Sheet for Subject ID __________

	Mid-Period Status					Period Results						
Period	**Cash**	**Initial Coupons**	**Coupons After Initial Trading**	**Added Coupons**	**Coupons for Final Trading**	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1		1		0					1220			Practice
2		1		0					1220			Practice
1		1		0					1220			
2		1		0					1220			
3		1		0					1220			
4		1		0					1220			
5		1		0					1220			
6		1		0					1220			
7		1		0					1220			
8		1		0					1220			
9		1		0					1220			
10		1		0					1220			
11		1		0					1220			
12		1		0					1220			
									Conversion Rate →	Total Profits / 200	Converted Total →	

Personal Record Sheet for Subject ID ________

	Mid-Period Status					Period Results							
Period	**Cash**	**Initial Coupons**	**Coupons After Initial Trading**	**Added Coupons**	**Coupons for Final Trading**	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1		0		1					1160			Practice
2		0		1					1160			Practice
1		0		1					1160			
2		0		1					1160			
3		0		1					1160			
4		0		1					1160			
5		0		1					1160			
6		0		1					1160			
7		0		1					1160			
8		0		1					1160			
9		0		1					1160			
10		0		1					1160			
11		0		1					1160			
12		0		1					1160			
									Conversion Rate →	Total Profits / 200	Converted Total →	

Personal Record Sheet for Subject ID _________

	Mid-Period Status					Period Results						
Period	**Cash**	**Initial Coupons**	**Coupons After Initial Trading**	**Added Coupons**	**Coupons for Final Trading**	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1		1		0					1150			Practice
2		1		0					1150			Practice
1		1		0					1150			
2		1		0					1150			
3		1		0					1150			
4		1		0					1150			
5		1		0					1150			
6		1		0					1150			
7		1		0					1150			
8		1		0					1150			
9		1		0					1150			
10		1		0					1150			
11		1		0					1150			
12		1		0					1150			
									Conversion Rate →	Total Profits / 200	Converted Total →	

Personal Record Sheet for Subject ID ________

	Mid-Period Status					Period Results						
Period	**Cash**	**Initial Coupons**	**Coupons After Initial Trading**	**Added Coupons**	**Coupons for Final Trading**	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1		0		1					1120			Practice
2		0		1					1120			Practice
1		0		1					1120			
2		0		1					1120			
3		0		1					1120			
4		0		1					1120			
5		0		1					1120			
6		0		1					1120			
7		0		1					1120			
8		0		1					1120			
9		0		1					1120			
10		0		1					1120			
11		0		1					1120			
12		0		1					1120			
									Conversion Rate →	Total Profits / 200	Converted Total →	

Personal Record Sheet for Subject ID ________

	Mid-Period Status					Period Results							
Period	Cash	Initial Coupons	Coupons After Initial Trading	Added Coupons	Coupons for Final Trading	Coupons Held (End of Period)	Actual Production	Total Production Costs	Fixed Period Revenue	Coupon Proceeds - Spent	Period Profits	Total Profits
1		5		4					240			Practice
2		5		4					240			Practice
1		5		4					240			
2		5		4					240			
3		5		4					240			
4		5		4					240			
5		5		4					240			
6		5		4					240			
7		5		4					240			
8		5		4					240			
9		5		4					240			
10		5		4					240			
11		5		4					240			
12		5		4					240			
									Conversion Rate →	Total Profits / 200	Converted Total →	

Personal Record Sheet for Subject ID _________

	Mid-Period Status					Period Results						
Period	**Cash**	**Initial Coupons**	**Coupons After Initial Trading**	**Added Coupons**	**Coupons for Final Trading**	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1		5		4					220			Practice
2		5		4					220			Practice
1		5		4					220			
2		5		4					220			
3		5		4					220			
4		5		4					220			
5		5		4					220			
6		5		4					220			
7		5		4					220			
8		5		4					220			
9		5		4					220			
10		5		4					220			
11		5		4					220			
12		5		4					220			
									Conversion Rate →	Total Profits / 200	Converted Total →	

Personal Record Sheet for Subject ID ________

	Mid-Period Status					Period Results						
Period	**Cash**	**Initial Coupons**	**Coupons After Initial Trading**	**Added Coupons**	**Coupons for Final Trading**	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1		4		5					150			Practice
2		4		5					150			Practice
1		4		5					150			
2		4		5					150			
3		4		5					150			
4		4		5					150			
5		4		5					150			
6		4		5					150			
7		4		5					150			
8		4		5					150			
9		4		5					150			
10		4		5					150			
11		4		5					150			
12		4		5					150			
									Conversion Rate →	Total Profits / 200	Converted Total →	

Personal Record Sheet for Subject ID ________

	Mid-Period Status					Period Results						
Period	Cash	Initial Coupons	Coupons After Initial Trading	Added Coupons	Coupons for Final Trading	Coupons Held (End of Period)	Actual Production	Total Production Costs	Fixed Period Revenue	Coupon Proceeds - Spent	Period Profits	Total Profits
1		4		5					190			Practice
2		4		5					190			Practice
1		4		5					190			
2		4		5					190			
3		4		5					190			
4		4		5					190			
5		4		5					190			
6		4		5					190			
7		4		5					190			
8		4		5					190			
9		4		5					190			
10		4		5					190			
11		4		5					190			
12		4		5					190			
									Conversion Rate →	Total Profits / 200	Converted Total →	

Appendix E Subject Instructions for Baseline Design

Instructions

General

This is an experiment in the economics of decision making. The instructions are simple and if you follow them carefully and make good decisions you will earn money that will be paid to you privately in cash. All earnings on your computer screens are in Experimental Dollars. These Experimental Dollars will be converted to real Dollars at the end of the experiment, at a rate of __180__ Experimental Dollars = 1 real Dollar. Notice that the more Experimental Dollars that you earn, the more cash that you receive at the end of the experiment.

We are going to conduct a number of periods. Attached to these instructions you will find a sheet labeled Personal Record Sheet, which will help you keep track of how your decisions impact your earnings. You are not to reveal this information to anyone. It is your own private information.

Each period you will produce units of a good. For every unit of the good that you produce, you will incur a production cost which will take away from your earnings. In order to avoid these costs, you may wish to purchase "coupons." Each coupon allows you to produce 1 less unit of the good.

At the beginning of each period you will receive cash in the form of a Fixed Period Revenue, and you may receive some coupons as well. There will then be a coupon trading stage during which time you may purchase or sell coupons with other participants. At the end of each period you will pay your production costs. Your earnings each period are determined as follows:

Earnings = Fixed Period Revenue – Total Production Costs

+ Sale Proceeds from Selling Coupons – Amount Spent when Buying Coupons.

Your Fixed Period Revenue does not depend on any actions you take, and does not change throughout the experiment. (In fact, it is already written on your Personal Record Sheet.) You will receive this revenue at the beginning of each period so that you have cash available with which to trade.

Production Costs

You must pay production costs when you produce units. The cost of each unit produced is typically different from the cost of other units produced, and your costs may or may not be different from the costs of other participants. Your production costs are always shown on the left side of your computer screen, as illustrated in Figure 1 (the numbers on this example screen are different from the actual numbers used in the experiment, and you won't actually learn your values until the experiment begins). Everyone can produce up to 10 units, and the cost of each unit is written separately.

For example, based on the numbers shown in the *example* in Figure 1, your first unit produced would cost 100, your second unit produced would cost 200, etc. If, for example, these were your production costs and you produced 3 units, your **total** costs would be 100+200+300=600. So you must recognize that the costs shown on your screen are the **extra** costs associated with each **additional** unit produced.

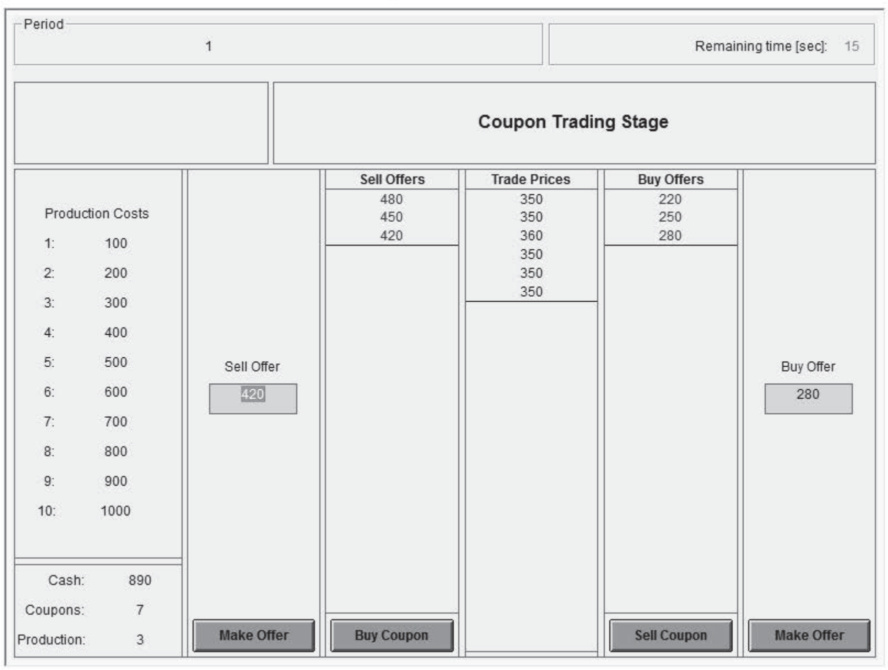


Figure 1

Coupons

We've already explained that your Fixed Period Revenue never changes, but your costs increase when you increase production. So why should you ever produce any units? The reason comes from today's compliance rule:

Compliance Rule: The sum of your production amount + coupons must equal 10

This rule means that you can avoid production (and save on your production costs) by holding coupons. Anyone can adjust their own holding of coupons by buying and selling them in a market that will operate over the computer network. If you sell coupons your cash increases by the sale amount, and if you buy coupons your cash decreases by the sale amount. Later in these instructions we explain the rules for buying and selling coupons.

Why might you want to buy a coupon? Remember that coupons allow you to avoid production, and they are always applied to the most expensive production first. If you currently hold 7 coupons, for example, and if you had the example production costs shown in Figure 1, then the last unit that you are supposed to produce is the 3rd unit (so that your production of 3 + coupons of 7 = 10). The production cost of this 3rd unit is 300. So if you can buy a coupon for less than 300, this might be a good idea since it allows you to save the production cost of 300. For example, if you bought one additional coupon for 280, you save the production cost of 300 and therefore make a profit (because of the lower costs that you need to incur) of 300-280=20.

Why might you want to sell a coupon? Continuing the illustration based on the example production costs shown in Figure 1, suppose that you currently still hold 7 coupons and the cost of the last unit produced is still 300. If you had 1 less coupon, the cost of the next unit produced (the 4th unit) would be 400. If you can sell a coupon for more than 400, this might be a good idea since these sales revenues exceed the production costs of this 4th unit. For example, if you sell a coupon for 420, even if you incur the additional (4th unit) production cost of 400 you would still make a profit on this sale of 420-400=20.

Period Results

Once trading has been completed, the results of the period will display on the screen. You should copy this information onto your Personal Record Sheet at the end of each period, and then click "continue" to begin the next period.

Figure 2 provides an example of the information provided in the period results. In this example, you have accumulated 7 coupons and are therefore are required to produce 3 units of the good based on the compliance rule (7 coupons + 3 units produced = 10). Your actual production level is determined automatically by the computer using this compliance rule.

Since you produced 3 units of the good, your total production costs are the sum of the costs for each of the first three units (100 + 200 + 300 = 600). Note that your production costs are still listed on this page in order to help you assess your strategies for buying and selling coupons during the trading stages. Lastly, your period and total profits are provided.

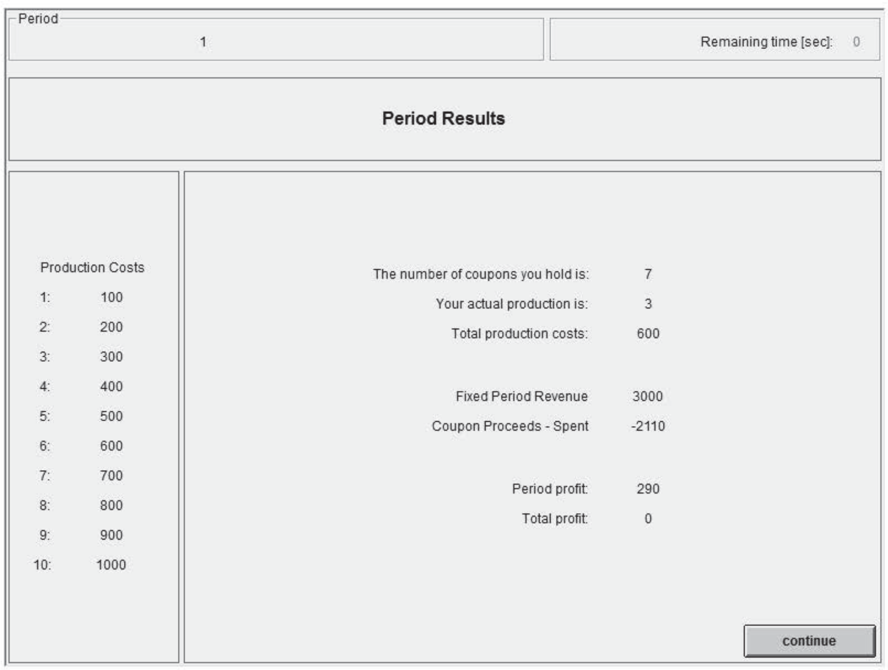


Figure 2

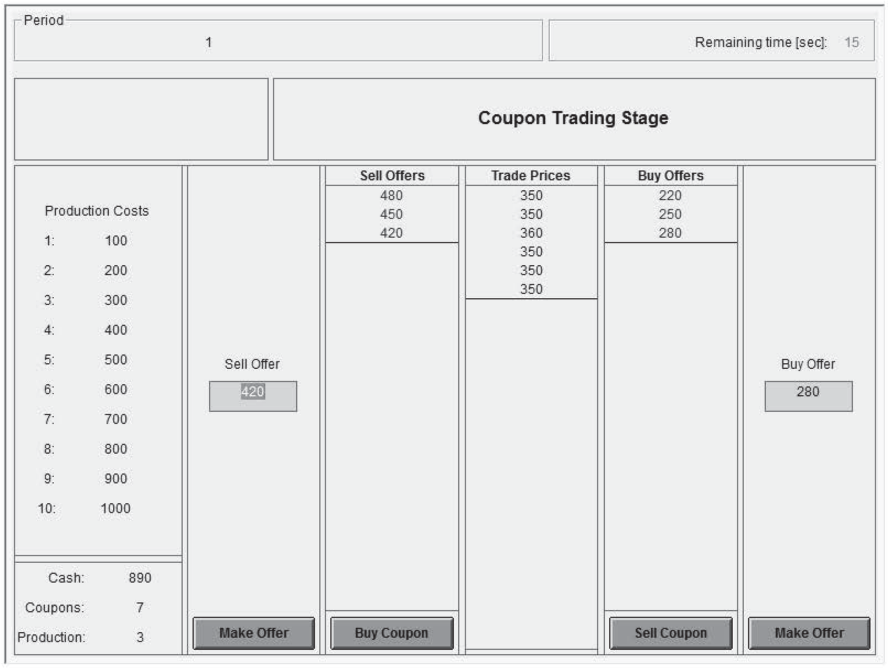
Coupon Trading Stage: How to Buy and Sell Coupons

During the trading stage, coupons can be purchased from and sold to other participants. At any time during the trading stage, everyone is free to make an offer to buy a coupon at a price they choose; likewise, everyone is free to make an offer to sell a coupon at a price they choose. Also at any time during the period, everyone is free to buy at the best offer price specified by someone wishing to sell, and everyone is free to sell at the best offer price specified by someone wishing to buy. (Of course, there are some limits: to sell a unit or make a sales offer, you need to have a coupon to sell. And to buy a unit or make a buy offer, you need to have enough cash to pay.)

You will enter offer prices and accept prices to execute transactions using your computer. Figure 1 (displayed again below for your convenience) shows the market trading screen for the Coupon Trading Stage. The time left in the period is shown on the upper right of the trading screen. You will have 3 minutes to buy and/or sell coupons each period.

Buying coupons

Participants interested in buying can submit offer prices using the "Buy Offer" box in the right side of the screen, and then clicking on the "Make Offer" button in the lower right. This offer price is immediately displayed on all traders' computers on the upper right part of the screen, labelled "Buy Offers." Once this offer price has been submitted, it is binding in the sense that anyone wishing to sell can accept this price offer. Such an acceptance results in an immediate trade at that price. The previous trading prices in the current period are displayed in the "Trading Prices" list in the center of your computer screen.



Repeat of Figure 1

If there are already Buy Offers displayed in the current period, then new buy offers submitted by anyone wishing to buy must provide better trading terms to the sellers. Sellers prefer higher prices, so any new buy offers must be higher than the current highest buy offer. Your computer will give you an error message if you try to offer a lower price than the best price currently available.

Another way to buy coupons is with the "Buy Coupon" button. Anyone wishing to buy can accept the best (that is, lowest) sell offer price by simply clicking the "Buy Coupon" button on the bottom of their computer screen. This results in an immediate trade at that price.

Regardless of how you buy coupons, your coupon and cash totals will be updated at the time of purchase. You can always find these totals in the bottom left of the screen, along with your production level if you maintain your current level of coupons.

Selling Coupons

Participants interested in selling can submit offer prices using the "Sell Offer" box on the left side of the screen, and then clicking on the "Make Offer" button below this box. This offer price is immediately displayed on all traders' computers on the left part of the screen, labelled "Sell Offers." Once this offer price has been submitted, it is binding in the sense that anyone wishing to buy can accept this price offer. Such an acceptance results in an immediate trade at that price.

If there are already Sell Offers displayed in the current period, then new sell offers submitted by anyone wishing to sell must provide better trading terms to the buyers. Buyers prefer lower prices, so any new sell offers must be lower than the current lowest sell offer. Your computer will give you an error message if you try to offer a higher price than the best price currently available.

Another way to sell coupons is with the "Sell Coupon" button. Anyone wishing to sell can accept the best (that is, highest offer price) by simply clicking the "Sell Coupon" button on the bottom of their computer screen. This results in an immediate trade at that price.

Regardless of how you sell coupons, your coupon and cash totals will be updated at the time of sale. You can always find these totals in the bottom left of the screen, along with your production level if you maintain your current level of coupons.

Summary

- Your production costs shown on the left of your computer screen are the extra, additional costs incurred for each unit that you produce.
- To be in compliance, your coupons + units produced = 10.
- During the Coupon Trading Stage, coupons can be purchased or sold by anyone at any price..
- Your current cash and coupon holdings, as well as the corresponding production level, are always provided during trading on the bottom left of your computer screen.
- You may be provided with coupons at the beginning of each period.
- Your coupon holdings, actual production level, and period profits will be provided during the Period Results stage at the end of each period. No coupons or cash will be carried over into the next period for use in trading.

This experiment will consist of 2 practice periods followed by 12 identical paid periods. Please note that while you cannot purchase coupons if you do not hold enough cash, you can have a negative profit for a period if your production costs are greater than your available cash after trading. Once we begin the experiment you should be careful to maintain positive cash holdings, since anyone whose period profit is below zero for 3 consecutive periods will be considered bankrupt and will no longer be allowed to participate in the experiment.

If you have any questions during the experiment, please raise your hand and I will come to your terminal. Are there any questions now before we begin the experiment?

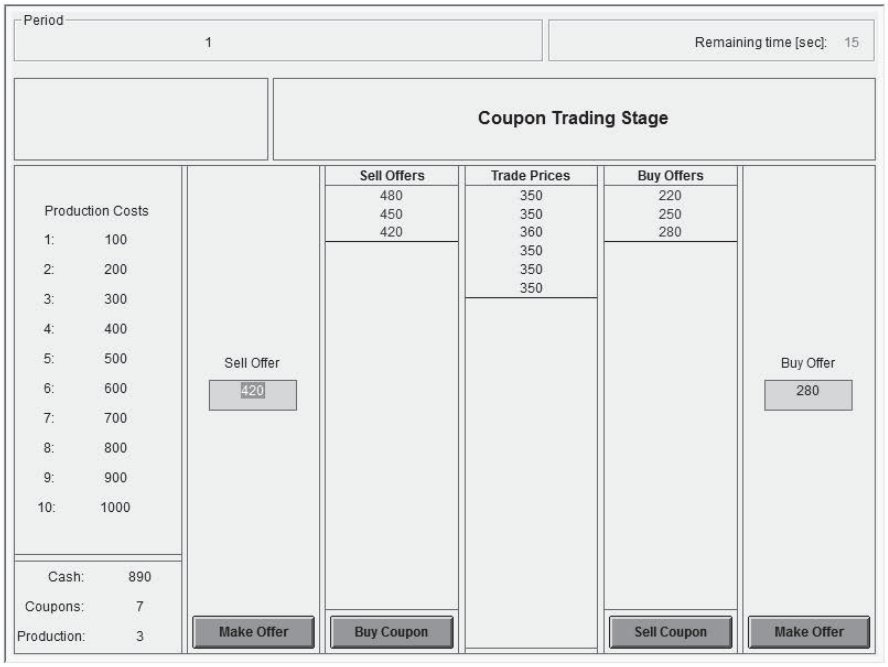

Period
1
Remaining time [sec]: 15
Coupon Trading Stage
Production Costs
1: 100
2: 200
3: 300
4: 400
5: 500
6: 600
7: 700
8: 800
9: 900
10: 1000
Cash: 890
Coupons: 7
Production: 3
Sell Offer
420
Make Offer
Sell Offers
480
450
420
Buy Coupon
Trade Prices
350
350
360
350
350
350
Buy Offers
220
250
280
Sell Coupon
Buy Offer
280
Make Offer

Figure 1

Personal Record Sheet for Subject ID _________

	Period Results						
Period	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1				1100			0 (practice)
2				1100			0 (practice)
1				1100			
2				1100			
3				1100			
4				1100			
5				1100			
6				1100			
7				1100			
8				1100			
9				1100			
10				1100			
11				1100			
12				1100			
				Conversion Rate →	Total Profits / 180	Converted Total →	

Personal Record Sheet for Subject ID _________

	Period Results						
Period	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1				1040			0 (practice)
2				1040			0 (practice)
1				1040			
2				1040			
3				1040			
4				1040			
5				1040			
6				1040			
7				1040			
8				1040			
9				1040			
10				1040			
11				1040			
12				1040			
				Conversion Rate →	Total Profits / 180	Converted Total →	

Personal Record Sheet for Subject ID _________

	Period Results						
Period	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1				1030			0 (practice)
2				1030			0 (practice)
1				1030			
2				1030			
3				1030			
4				1030			
5				1030			
6				1030			
7				1030			
8				1030			
9				1030			
10				1030			
11				1030			
12				1030			
				Conversion Rate →	Total Profits / 180	Converted Total →	

Personal Record Sheet for Subject ID _________

	Period Results						
Period	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1				1020			0 (practice)
2				1020			0 (practice)
1				1020			
2				1020			
3				1020			
4				1020			
5				1020			
6				1020			
7				1020			
8				1020			
9				1020			
10				1020			
11				1020			
12				1020			
				Conversion Rate →	Total Profits / 180	Converted Total →	

Personal Record Sheet for Subject ID _________

	Period Results						
Period	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1				220			0 (practice)
2				220			0 (practice)
1				220			
2				220			
3				220			
4				220			
5				220			
6				220			
7				220			
8				220			
9				220			
10				220			
11				220			
12				220			
				Conversion Rate →	Total Profits / 180	Converted Total →	

Personal Record Sheet for Subject ID ________

	Period Results						
Period	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1				210			0 (practice)
2				210			0 (practice)
1				210			
2				210			
3				210			
4				210			
5				210			
6				210			
7				210			
8				210			
9				210			
10				210			
11				210			
12				210			
				Conversion Rate →	Total Profits / 180	Converted Total →	

Personal Record Sheet for Subject ID _________

	Period Results						
Period	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1				140			0 (practice)
2				140			0 (practice)
1				140			
2				140			
3				140			
4				140			
5				140			
6				140			
7				140			
8				140			
9				140			
10				140			
11				140			
12				140			
				Conversion Rate →	Total Profits / 180	Converted Total →	

Personal Record Sheet for Subject ID _________

	Period Results						
Period	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1				180			0 (practice)
2				180			0 (practice)
1				180			
2				180			
3				180			
4				180			
5				180			
6				180			
7				180			
8				180			
9				180			
10				180			
11				180			
12				180			
				Conversion Rate →	Total Profits / 180	Converted Total →	

Appendix F Subject Instructions for Hard Ceiling Design

Instructions

General

This is an experiment in the economics of decision making. The instructions are simple and if you follow them carefully and make good decisions you will earn money that will be paid to you privately in cash. All earnings on your computer screens are in Experimental Dollars. These Experimental Dollars will be converted to real Dollars at the end of the experiment, at a rate of 170 Experimental Dollars = 1 real Dollar. Notice that the more Experimental Dollars that you earn, the more cash that you receive at the end of the experiment.

We are going to conduct a number of periods. Attached to these instructions you will find a sheet labeled Personal Record Sheet, which will help you keep track of how your decisions impact your earnings. You are not to reveal this information to anyone. It is your own private information.

Each period you will produce units of a good. For every unit of the good that you produce, you will incur a production cost which will take away from your earnings. In order to avoid these costs, you may wish to purchase "coupons." Each coupon allows you to produce 1 less unit of the good.

At the beginning of each period you will receive cash in the form of a Fixed Period Revenue. There will then be two coupon trading stages during which time you may purchase or sell coupons with other participants. (Each of you will receive coupons before one or both trading stages so that you have something to trade.) At the end of each period you will pay your production costs. Your earnings each period are determined as follows:

Earnings = Fixed Period Revenue – Total Production Costs
+ Sale Proceeds from Selling Coupons – Amount Spent when Buying Coupons.

Your Fixed Period Revenue does not depend on any actions you take, and does not change throughout the experiment. (In fact, it is already written on your Personal Record Sheet.) You will receive this revenue at the beginning of each period so that you have cash available with which to trade.

Production Costs

You must pay production costs when you produce units. The cost of each unit produced is typically different from the cost of other units produced, and your costs may or may not be different from the costs of other participants. Your production costs are always shown on the left side of your computer screen, as illustrated in Figure 1 (the numbers on this example screen are different from the actual numbers used in the experiment, and you won't actually learn your values until the experiment begins). Everyone can produce up to 10 units, and the cost of each unit is written separately.

For example, based on the numbers shown in the *example* in Figure 1, your first unit produced would cost 100, your second unit produced would cost 200, etc. If, for example, these were your production costs and you produced 3 units, your **total** costs would be 100+200+300=600. So you must recognize that the costs shown on your screen are the **extra** costs associated with each **additional** unit produced.

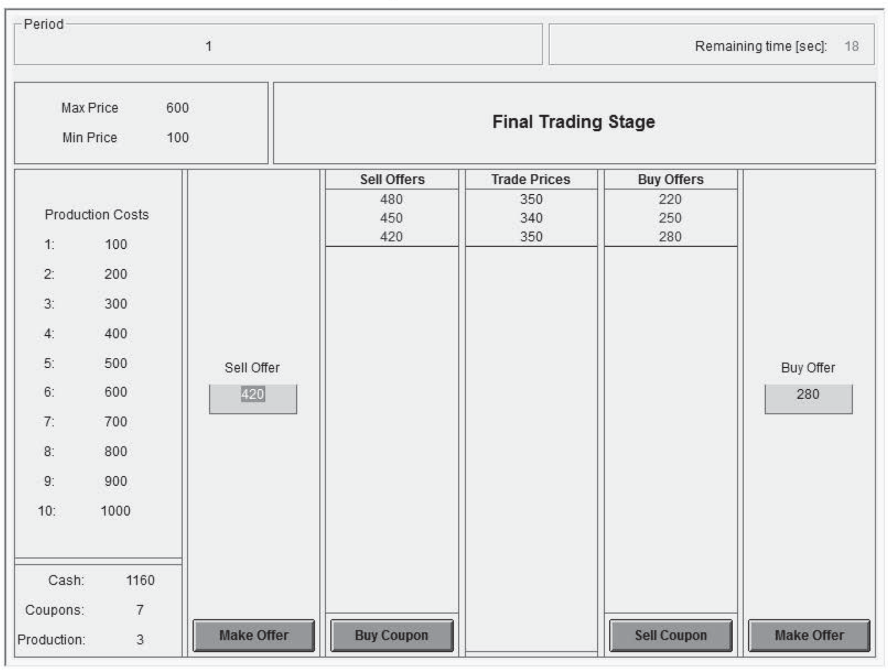


Figure 1

Coupons

We've already explained that your Fixed Period Revenue never changes, but your costs increase when you increase production. So why should you ever produce any units? The reason comes from today's compliance rule:

Compliance Rule: The sum of your production amount + coupons must equal 10

This rule means that you can avoid production (and save on your production costs) by holding coupons. Anyone can adjust their own holding of coupons by buying and selling them in a market that will operate over the computer network. If you sell coupons your cash increases by the sale amount, and if you buy coupons your cash decreases by the sale amount. Later in these instructions we explain the rules for buying and selling coupons.

Why might you want to buy a coupon? Remember that coupons allow you to avoid production, and they are always applied to the most expensive production first. If you currently hold 7 coupons, for example, and if you had the example production costs shown in Figure 1, then the last unit that you are supposed to produce is the 3rd unit (so that your production of 3 + coupons of 7 = 10). The production cost of this 3rd unit is 300. So if you can buy a coupon for less than 300, this might be a good idea since it allows you to save the production cost of 300. For example, if you bought one additional coupon for 280, you save the production cost of 300 and therefore make a profit (because of the lower costs that you need to incur) of 300-280=20.

Why might you want to sell a coupon? Continuing the illustration based on the example production costs shown in Figure 1, suppose that you currently still hold 7 coupons and the cost of the last unit produced is still 300. If you had 1 less coupon, the cost of the next unit produced (the 4th unit) would be 400. If you can sell a coupon for more than 400, this might be a good idea since these sales revenues exceed the production costs of this 4th unit. For example, if you sell a coupon for 420, even if you incur the additional (4th unit) production cost of 400 you would still make a profit on this sale of 420-400=20.

Coupon Trading Stage: How to Buy and Sell Coupons

During the trading stage, coupons can be purchased from and sold to other participants. At any time during the trading stage, everyone is free to make an offer to buy a coupon at a price they choose; likewise, everyone is free to make an offer to sell a coupon at a price they choose. Also at any time during the period, everyone is free to buy at the best offer price specified by someone wishing to sell, and everyone is free to sell at the best offer price specified by someone wishing to buy. (Of course, there are some limits: to sell a unit or make a sales offer, you need to have a coupon to sell. And to buy a unit or make a buy offer, you need to have enough cash to pay.)

You will enter offer prices and accept prices to execute transactions using your computer. Figure 1 (displayed again on a separate sheet for your convenience) shows the market trading screen for one of the coupon trading stages. The time left in the period is shown on the upper right of the trading screen. You will have 2 minutes to buy and/or sell coupons in each trading stage.

Buying coupons

Participants interested in buying can submit offer prices using the "Buy Offer" box in the right side of the screen, and then clicking on the "Make Offer" button in the lower right. This offer price is immediately displayed on all traders' computers on the upper right part of the screen, labelled "Buy Offers." Once this offer price has been submitted, it is binding in the sense that anyone wishing to sell can accept this price offer. Such an acceptance results in an immediate trade at that price. The previous trading prices in the current period are displayed in the "Trading Prices" list in the center of your computer screen.

If there are already Buy Offers displayed in the current period, then new buy offers submitted by anyone wishing to buy must provide better trading terms to the sellers. Sellers prefer higher prices, so any new buy offers must be higher than the current highest buy offer. Your computer will give you an error message if you try to offer a lower price than the best price currently available.

Another way to buy coupons is with the "Buy Coupon" button. Anyone wishing to buy can accept the best (that is, lowest) sell offer price by simply clicking the "Buy Coupon" button on the bottom of their computer screen. This results in an immediate trade at that price.

Regardless of how you buy coupons, your coupon and cash totals will be updated at the time of purchase. You can always find these totals in the bottom left of the screen, along with your production level if you maintain your current level of coupons.

Selling Coupons

Participants interested in selling can submit offer prices using the "Sell Offer" box on the left side of the screen, and then clicking on the "Make Offer" button below this box. This offer price is immediately displayed on all traders' computers on the left part of the screen, labelled "Sell Offers." Once this offer price has been submitted, it is binding in the sense that anyone wishing to buy can accept this price offer. Such an acceptance results in an immediate trade at that price.

If there are already Sell Offers displayed in the current period, then new sell offers submitted by anyone wishing to sell must provide better trading terms to the buyers. Buyers prefer lower prices, so any new sell offers must be lower than the current lowest sell offer. Your computer will give you an error message if you try to offer a higher price than the best price currently available.

Another way to sell coupons is with the "Sell Coupon" button. Anyone wishing to sell can accept the best (that is, highest offer price) by simply clicking the "Sell Coupon" button on the bottom of their computer screen. This results in an immediate trade at that price.

Regardless of how you sell coupons, your coupon and cash totals will be updated at the time of sale. You can always find these totals in the bottom left of the screen, along with your production level if you maintain your current level of coupons.

Period Structure

This experiment will consist of 2 practice periods followed by 12 paid periods. Each period is identical and will include the following steps in Figure 2:

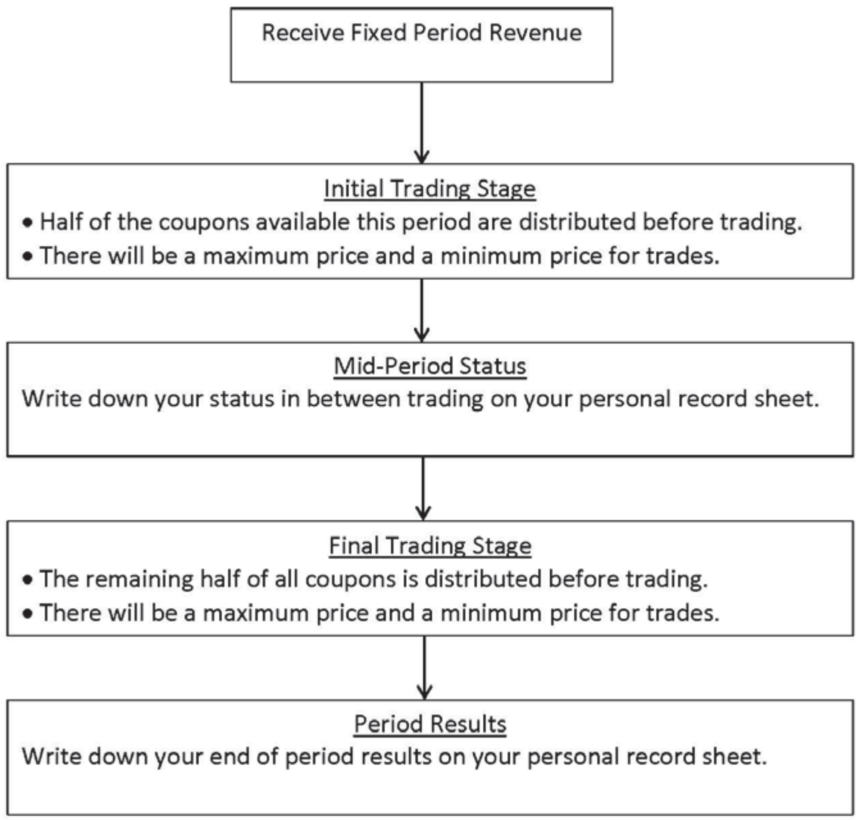


Figure 2

Initial Trading Stage

During each period, you will have two separate trading stages during which you may choose to buy and/or sell coupons, an "Initial Trading Stage" and a "Final Trading Stage," each lasting 2 minutes. Each trading stage will also have a "Min Price," which is the minimum or lowest price at which a coupon can be purchased or sold, and a "Max Price," which is the maximum or highest price for coupon trading. This information is located in the top-left section of your trading screen (Figure 3).

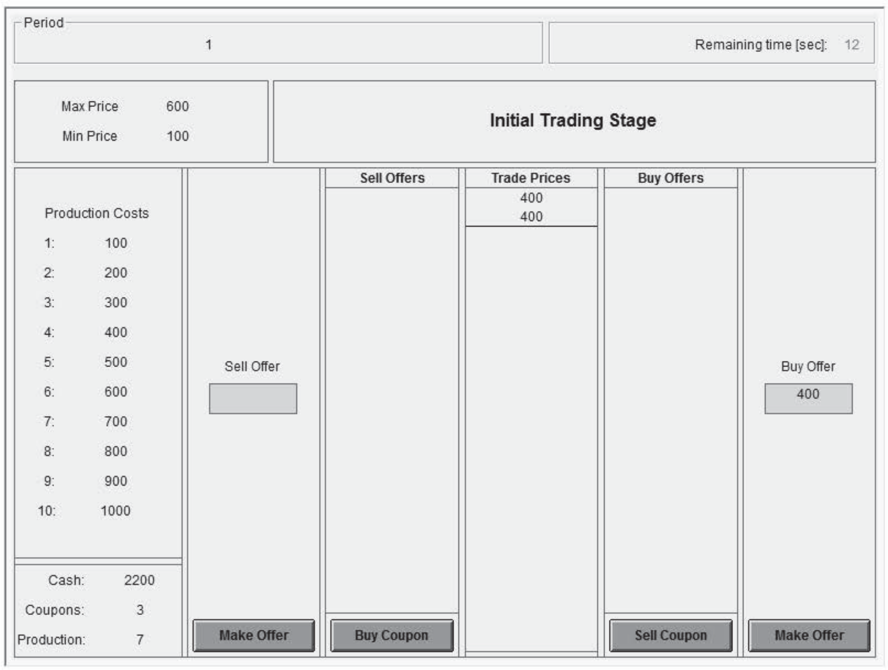


Figure 3

In the example in Figure 3, you would be trading in the Initial Trading Stage with a minimum price of 100 and a maximum price of 600.

Mid-Period Status

Each period, coupons will be distributed to participants at the beginning of both trading stages. Half of all coupons will be distributed amongst participants before the Initial Trading Stage, with the remaining half distributed before the Final Trading Stage. (Your personal coupon amounts are already on your record sheet.) The Mid-Period Status screen (Figure 4) will provide you with a summary of your coupon levels. You will enter this on your record sheet.

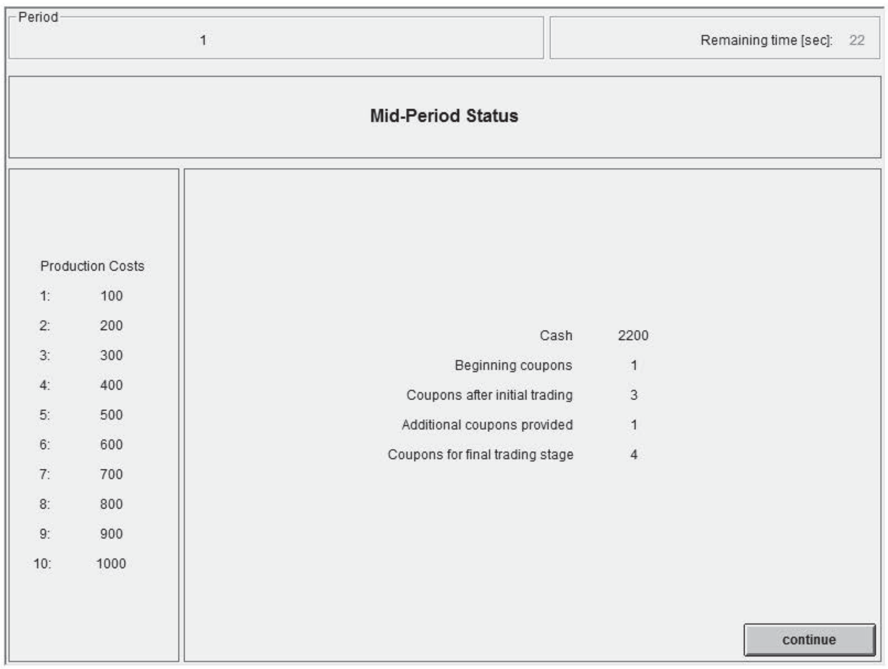


Figure 4

In this example, you started the Initial Trading Stage with 1 coupon and held 3 coupons after initial trading was complete. You receive 1 additional coupon, bringing your total coupons to 4 for the start of the Final Trading Stage.

Once you have recorded the Mid-Period Status information, you can hit the continue button.

Final Trading Stage

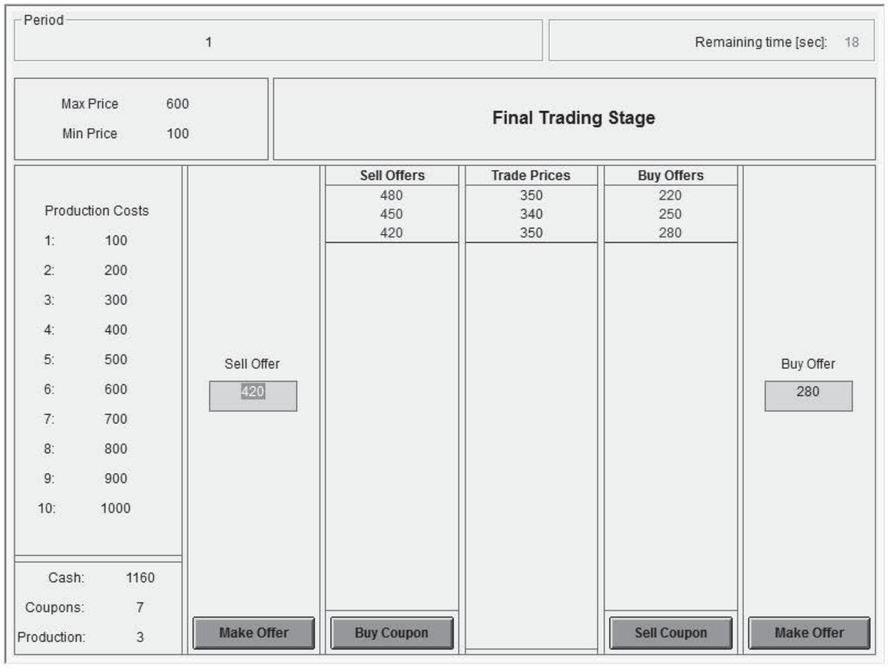


Figure 1 (repeat)

The Final Trading Stage screen is similar to the initial trading screen.

Period Results

Once trading has been completed, the results of the period will display on the screen. You should copy this information onto your Personal Record Sheet at the end of each period, and then click “continue” to begin the next period.

Figure 2 provides an example of the information provided in the period results. In this example, you have accumulated 7 coupons and are therefore required to produce 3 units of the good based on the compliance rule (7 coupons + 3 units produced = 10). Your actual production level is determined automatically by the computer using this compliance rule.

Since you produced 3 units of the good, your total production costs are the sum of the costs for each of the first three units (100 + 200 + 300 = 600). Note that your production costs are still listed on this page in order to help you assess your strategies for buying and selling coupons during the trading stages. Lastly, your period and total profits are provided.

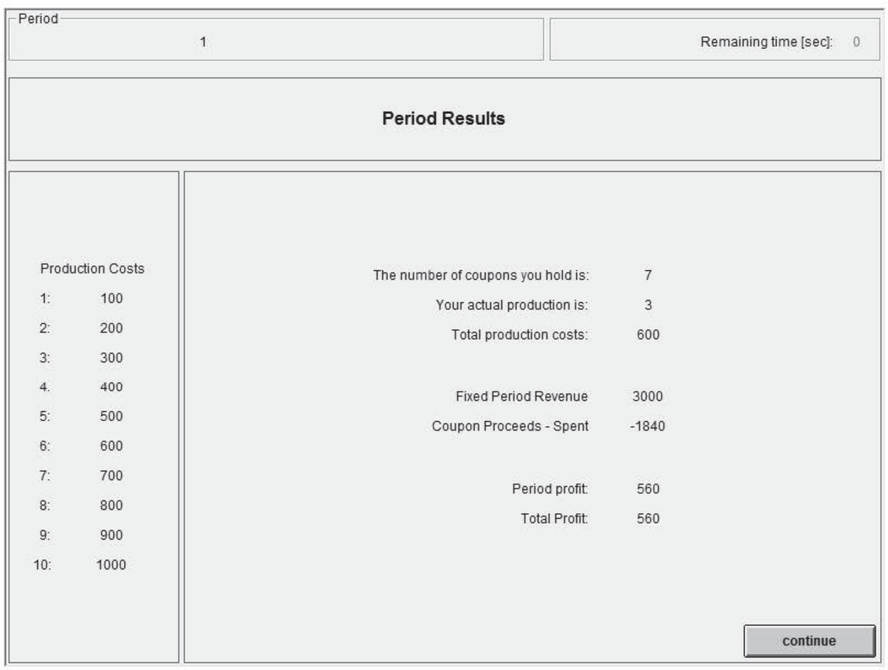


Figure 5

Summary

- Your production costs shown on the left of your computer screen are the extra, additional costs incurred for each unit that you produce.
- To be in compliance, your coupons + units produced = 10.
- There will be 2 trading stages. During either trading stage, coupons can be purchased or sold by anyone at any price above the Min Price and below the Max Price listed on the screen. The Min Price and Max Price will be identical for both trading stages.
- Half of all coupons will be distributed before initial trading with the remaining half distributed before final trading. You might be provided with coupons at the beginning of either trading stage during each period.
- Your current cash and coupon holdings, as well as the corresponding production level, are always provided during trading on the bottom left of your computer screen.
- Your coupon receipts and changes in coupon levels will be provided during the Mid-Period Results stage in between the 2 trading stages.
- Your coupon holdings, actual production level, and period profits will be provided during the Period Results stage at the end of each period. No coupons or cash will be carried over into the next period for use in trading.

Please note that while you cannot purchase coupons if you do not hold enough cash, you can have a negative profit for a period if your production costs are greater than your available cash after trading. Once we begin the experiment you should be careful to maintain positive cash holdings, since anyone whose period profit is below zero for 3 consecutive periods will be considered bankrupt and will no longer be allowed to participate in the experiment.

If you have any questions during the experiment, please raise your hand and I will come to your terminal. Are there any questions now before we begin the experiment?

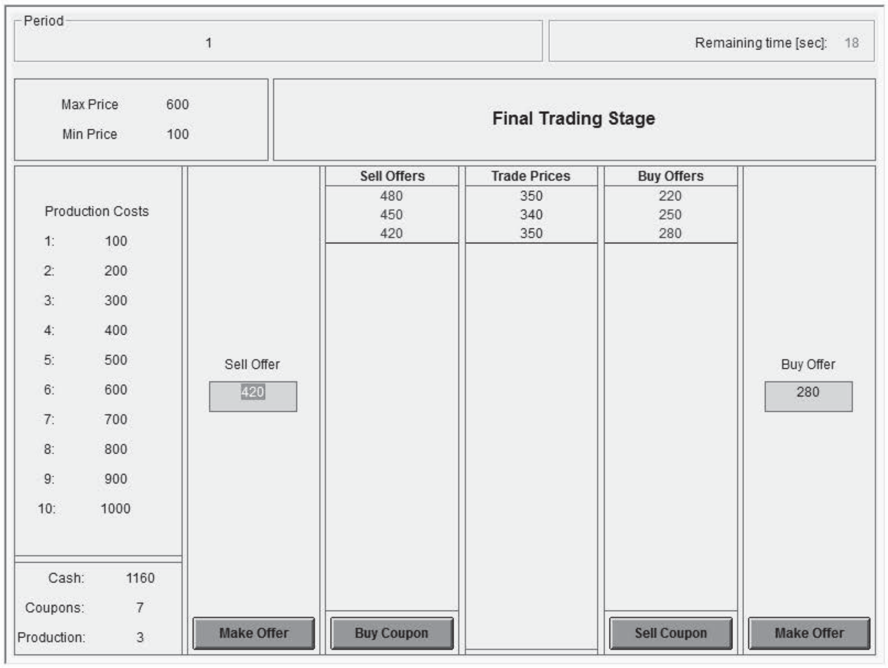

Period
1
Remaining time [sec]: 18
Max Price 600
Min Price 100
Final Trading Stage
Production Costs
1: 100
2: 200
3: 300
4: 400
5: 500
6: 600
7: 700
8: 800
9: 900
10: 1000
Cash: 1160
Coupons: 7
Production: 3
Sell Offer
420
Make Offer
Sell Offers
480
450
420
Buy Coupon
Trade Prices
350
340
350
Buy Offers
220
250
280
Sell Coupon
Buy Offer
280
Make Offer

Figure 1

Personal Record Sheet for Subject ID _________

	Mid-Period Status					Period Results						
Period	**Cash**	**Initial Coupons**	**Coupons After Initial Trading**	**Added Coupons**	**Coupons for Final Trading**	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1		1		0					1100			Practice
2		1		0					1100			Practice
1		1		0					1100			
2		1		0					1100			
3		1		0					1100			
4		1		0					1100			
5		1		0					1100			
6		1		0					1100			
7		1		0					1100			
8		1		0					1100			
9		1		0					1100			
10		1		0					1100			
11		1		0					1100			
12		1		0					1100			
									Conversion Rate →	Total Profits / 170	Converted Total →	

Personal Record Sheet for Subject ID ________

	Mid-Period Status					Period Results						
Period	**Cash**	**Initial Coupons**	**Coupons After Initial Trading**	**Added Coupons**	**Coupons for Final Trading**	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1		0		1					1040			Practice
2		0		1					1040			Practice
1		0		1					1040			
2		0		1					1040			
3		0		1					1040			
4		0		1					1040			
5		0		1					1040			
6		0		1					1040			
7		0		1					1040			
8		0		1					1040			
9		0		1					1040			
10		0		1					1040			
11		0		1					1040			
12		0		1					1040			
									Conversion Rate →	Total Profits / 170	Converted Total →	

Personal Record Sheet for Subject ID ________

	Mid-Period Status					Period Results						
Period	**Cash**	**Initial Coupons**	**Coupons After Initial Trading**	**Added Coupons**	**Coupons for Final Trading**	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1		1		0					1030			Practice
2		1		0					1030			Practice
1		1		0					1030			
2		1		0					1030			
3		1		0					1030			
4		1		0					1030			
5		1		0					1030			
6		1		0					1030			
7		1		0					1030			
8		1		0					1030			
9		1		0					1030			
10		1		0					1030			
11		1		0					1030			
12		1		0					1030			
									Conversion Rate →	Total Profits / 170	Converted Total →	

Personal Record Sheet for Subject ID ________

	Mid-Period Status					Period Results							
Period	Cash	Initial Coupons	Coupons After Initial Trading	Added Coupons	Coupons for Final Trading	Coupons Held (End of Period)	Actual Production	Total Production Costs	Fixed Period Revenue	Coupon Proceeds - Spent	Period Profits	Total Profits
1		0		1					1020			Practice
2		0		1					1020			Practice
1		0		1					1020			
2		0		1					1020			
3		0		1					1020			
4		0		1					1020			
5		0		1					1020			
6		0		1					1020			
7		0		1					1020			
8		0		1					1020			
9		0		1					1020			
10		0		1					1020			
11		0		1					1020			
12		0		1					1020			
									Conversion Rate →	Total Profits / 170	Converted Total →	

Personal Record Sheet for Subject ID ________

	Mid-Period Status					Period Results						
Period	**Cash**	**Initial Coupons**	**Coupons After Initial Trading**	**Added Coupons**	**Coupons for Final Trading**	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1		5		4					220			Practice
2		5		4					220			Practice
1		5		4					220			
2		5		4					220			
3		5		4					220			
4		5		4					220			
5		5		4					220			
6		5		4					220			
7		5		4					220			
8		5		4					220			
9		5		4					220			
10		5		4					220			
11		5		4					220			
12		5		4					220			
									Conversion Rate →	Total Profits / 170	Converted Total →	

Personal Record Sheet for Subject ID ________

	Mid-Period Status					Period Results						
Period	**Cash**	**Initial Coupons**	**Coupons After Initial Trading**	**Added Coupons**	**Coupons for Final Trading**	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1		5		4					210			Practice
2		5		4					210			Practice
1		5		4					210			
2		5		4					210			
3		5		4					210			
4		5		4					210			
5		5		4					210			
6		5		4					210			
7		5		4					210			
8		5		4					210			
9		5		4					210			
10		5		4					210			
11		5		4					210			
12		5		4					210			
									Conversion Rate →	Total Profits / 170	Converted Total →	

Personal Record Sheet for Subject ID _________

	Mid-Period Status					Period Results						
Period	Cash	Initial Coupons	Coupons After Initial Trading	Added Coupons	Coupons for Final Trading	Coupons Held (End of Period)	Actual Production	Total Production Costs	Fixed Period Revenue	Coupon Proceeds - Spent	Period Profits	Total Profits
1		4		5					140			Practice
2		4		5					140			Practice
1		4		5					140			
2		4		5					140			
3		4		5					140			
4		4		5					140			
5		4		5					140			
6		4		5					140			
7		4		5					140			
8		4		5					140			
9		4		5					140			
10		4		5					140			
11		4		5					140			
12		4		5					140			
									Conversion Rate →	Total Profits / 170	Converted Total →	

Personal Record Sheet for Subject ID ________

	Mid-Period Status					Period Results						
Period	**Cash**	**Initial Coupons**	**Coupons After Initial Trading**	**Added Coupons**	**Coupons for Final Trading**	**Coupons Held (End of Period)**	**Actual Production**	**Total Production Costs**	**Fixed Period Revenue**	**Coupon Proceeds - Spent**	**Period Profits**	**Total Profits**
1		4		5					180			Practice
2		4		5					180			Practice
1		4		5					180			
2		4		5					180			
3		4		5					180			
4		4		5					180			
5		4		5					180			
6		4		5					180			
7		4		5					180			
8		4		5					180			
9		4		5					180			
10		4		5					180			
11		4		5					180			
12		4		5					180			
									Conversion Rate →	Total Profits / 170	Converted Total →	

VITA

VITA

With a bachelor's degree in chemical engineering from the University of Pennsylvania, research leadership positions in both industry (Procter & Gamble) and academia (University of North Carolina), and now a Ph.D. focused on energy and environmental economics, David Perkis brings a wealth of knowledge and experience to bear on his current research and teaching efforts in resource economics.

Before arriving at Purdue University, Dr. Perkis demonstrated leadership in an academic setting by managing a statistical and data support group which served the efforts of a major research center spanning the University of North Carolina system. In addition to managing a group of doctoral students and data managers, Dr. Perkis led efforts to coordinate and analyze both primary survey data and secondary data sources as part of a national home safety study, leading to a national report in conjunction with Lowe's Home Safety Council and five journal publications.

During his studies at Purdue University, Dr. Perkis has received recognition for his work in policy analysis (http://www.purdue.edu/fivestudents/policy/perkis.html), often incorporating engineering models within economic analytical methods to obtain robust results. These efforts have led to publications in both engineering and economic policy journals. More recently, his research has utilized experimental economic methods to determine the effectiveness of price controls in emissions permit markets. This research found that some of the more recently developed mechanisms may be ineffective in hitting theoretical targets under certain conditions (published this year in Environmental and Resource Economics and in Chapter 4 of this dissertation). Currently, Dr. Perkis is utilizing Markal equilibrium energy models to study the interactions between emissions and energy security objectives in the United States.

Dr. Perkis has also gained recognition for his skills as a university instructor, having won top teaching awards in the College of Agriculture at Purdue and the award for the top graduate instructor in the Agricultural & Applied Economics Association. He is passionate about issues related to economic and financial education, and has successfully incorporated experimental economic techniques with student-focused learning methods to encourage active learning and increase student participation in the classroom. Dr. Perkis currently teaches roughly four hundred students each semester, manages several undergraduate and graduate teaching assistants, and is actively involved in transforming the department's entry level course in agribusiness in order to increase student engagement.

For a detailed list of publications and awards, please see his CV here: http://web.ics.purdue.edu/~perkis/cv-perkis.pdf