DYNAMIC OPTIMIZATION MODEL
FOR A LIGNOCELLULOSIC BIOREFINERY SUPPLY CHAIN

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by
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Lignocellulosic biorefining system studies have not adequately addressed the integrated nature of the supply chain from feedstock source (farms) to product demand points. The literature typically focuses on systems of single processing facilities with a tendency to study the agricultural side of the supply chain and dismiss the product distribution considerations, such as proximity to demand centers, other processing facilities, or the nature of product market demand.

This study offers a more holistic approach by modeling the supply chain from multiple agricultural production sources (farms) to multiple biorefineries, as well as the product distribution to multiple demand locations. The objectives are to establish a dynamic modeling framework for a biorefinery supply chain and to illustrate the use of that framework. The model is designed with the following considerations in mind. 1) Which feedstocks should be purchased? 2) When and from where should they be purchased? 3) Where, how much, and how long should feedstocks be stored? 4) Where, when, how many, and how large should the biorefineries be built? 5) How much and when should the products be produced? 6) How much and where should the products be distributed? 7) How should processing capacity expand over time?

The modeling methodology employs a dynamic mathematical program. The supply chain is defined by a system of constraint expressions and optimized by maximizing total system profit. The profit function is defined to
include product revenue and system costs, such as feedstock costs, transportation costs, and operating costs. The factors influencing the parameterization of the model are discussed and example parameter values are given. The model is validated and executed to obtain an example solution. The results are presented and discussed to illustrate how the modeling framework can be used to help support biorefinery system planning decisions.

This original contribution shows that biorefinery supply chains modeled to incorporate the interactions between multiple farms, biorefineries, and demand locations can provide insights that would not be possible with single system studies or “supply side only” models. It is shown that mathematical programming offers useful tools for biorefinery supply chain studies. Topics for further research are discussed.
BIOGRAPHICAL SKETCH

Mr. Pack obtained his B.S. in Applied Science majoring in Engineering Management from Miami University, Oxford, Ohio in 2000. He also earned an M.S. in Agricultural and Biological Engineering from Cornell University in 2004.

Mr. Pack has held a number of full time and internship positions in gas and electric utilities, the pulp & paper industry, management consulting, and economic development in addition to his research interests in biobased industrial systems.
This is dedicated to my wife Jill, for her patience, love, and support of me as I completed this project.
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# TABLE OF CONTENTS

1.0 INTRODUCTION .................................................................................................................................1  
  1.1 Context ...........................................................................................................................................1  
  1.2 Background ......................................................................................................................................5  
    1.2.1 Key Questions .........................................................................................................................7  
  1.3 Literature Review ...........................................................................................................................10  
  1.4 Objectives and Definitions .............................................................................................................47  

2.0 MATHEMATICAL DECISION MODEL .............................................................................................52  
  2.1 System Scope ..................................................................................................................................53  
  2.2 Model Nomenclature .......................................................................................................................54  
  2.3 Constraints .....................................................................................................................................57  
  2.4 Objective Function ..........................................................................................................................65  
  2.5 Useful Model Extensions .................................................................................................................67  
    2.5.1 Facility Siting (Question #4) .................................................................................................67  
    2.5.2 Capacity Expansion (Question #7) .......................................................................................69  

3.0 DISCUSSION, COLLECTION, AND DEFINITION OF PARAMETER DATA ...............................72  
  3.1 Biorefinery Data ..............................................................................................................................72  
    3.1.1 Material Handling Requirements ...........................................................................................73  
    3.1.2 Total Initial Capacity ..............................................................................................................75  
    3.1.3 Material Conversion Factors .................................................................................................75  
    3.1.4 Construction and Startup Cost .............................................................................................78  
    3.1.5 Total Feedstock Costs ............................................................................................................81  
    3.1.6 Operating Costs .......................................................................................................................82  
  3.2 Agricultural Data .............................................................................................................................84  
    3.2.1 Treatment of Seasons .............................................................................................................85  
    3.2.2 Feedstock Availability ............................................................................................................86  
    3.2.3 Land Area Limit ......................................................................................................................88  
  3.3 Product Distribution Data ..............................................................................................................90  
    3.3.1 Product Demand .....................................................................................................................90  
    3.3.2 Product Revenue .....................................................................................................................91  
    3.3.3 Distribution Cost ....................................................................................................................93  
    3.3.4 Inventory Holding Cost .........................................................................................................94  
    3.3.5 Shortage Cost ..........................................................................................................................95  
  3.4 Spatial Modeling Considerations ....................................................................................................96  

4.0 SAMPLE COMPUTER IMPLEMENTATION AND SOLUTION ..................................................99  
  4.1 Optimization Software Package and Model Code ............................................................................99  
  4.2 Model Validation ............................................................................................................................100  
  4.3 Solution to Implementation Example and Analysis ..........................................................................103  
    4.3.1 High Level Economic Results ...............................................................................................105  
    4.3.2 Validation of Example Solution ............................................................................................107  
    4.3.3 Analysis of Individual System Components ..........................................................................111  
      4.3.3.1 Feedstock Harvest Results ............................................................................................113  
      4.3.3.2 Feedstock Storage Results ............................................................................................118
**LIST OF FIGURES**

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>System structure and model overview</td>
<td>55</td>
</tr>
<tr>
<td>2</td>
<td>Potential guidelines for spatial assumptions</td>
<td>98</td>
</tr>
<tr>
<td>3</td>
<td>Objective value and economic outcome from example</td>
<td>105</td>
</tr>
<tr>
<td>4</td>
<td>Farmland Harvested by Feedstock</td>
<td>114</td>
</tr>
<tr>
<td>5</td>
<td>Feedstock Harvested &amp; Shipped by Feedstock Type</td>
<td>114</td>
</tr>
<tr>
<td>6</td>
<td>Corn stover harvested &amp; shipped by farm of origin</td>
<td>116</td>
</tr>
<tr>
<td>7</td>
<td>Wheat straw harvested &amp; shipped by farm of origin</td>
<td>116</td>
</tr>
<tr>
<td>8</td>
<td>Corn stover shipped from farm k=2 by destination</td>
<td>117</td>
</tr>
<tr>
<td>9</td>
<td>Corn stover shipped from farm k=1 by destination</td>
<td>117</td>
</tr>
<tr>
<td>10</td>
<td>Wheat straw shipped from farm k=2 by destination</td>
<td>119</td>
</tr>
<tr>
<td>11</td>
<td>Wheat straw shipped from farm k=1 by destination</td>
<td>119</td>
</tr>
<tr>
<td>12</td>
<td>Feedstock storage by feedstock type</td>
<td>120</td>
</tr>
<tr>
<td>13</td>
<td>Feedstock storage at site i=1 by feedstock type</td>
<td>121</td>
</tr>
<tr>
<td>14</td>
<td>Feedstock storage at site i=2 by feedstock type</td>
<td>121</td>
</tr>
<tr>
<td>15</td>
<td>Feedstock storage at site i=3 by feedstock type</td>
<td>122</td>
</tr>
<tr>
<td>16</td>
<td>Feedstock processed at biorefinery site i=3 by feedstock</td>
<td>122</td>
</tr>
<tr>
<td>17</td>
<td>Feedstock processed by feedstock</td>
<td>123</td>
</tr>
<tr>
<td>18</td>
<td>Total feedstock processed by biorefinery</td>
<td>124</td>
</tr>
<tr>
<td>19</td>
<td>Total product manufacture by biorefinery</td>
<td>124</td>
</tr>
<tr>
<td>20</td>
<td>Total manufacturing by product</td>
<td>126</td>
</tr>
<tr>
<td>21</td>
<td>Succinic acid manufacturing by biorefinery</td>
<td>126</td>
</tr>
<tr>
<td>22</td>
<td>Succinic acid manufacturing at biorefinery site i=1</td>
<td>127</td>
</tr>
<tr>
<td>23</td>
<td>Total product inventory by biorefinery</td>
<td>128</td>
</tr>
<tr>
<td>24</td>
<td>Succinic acid inventory by biorefinery</td>
<td>131</td>
</tr>
<tr>
<td>25</td>
<td>Succinic acid inventory at biorefinery site i=1</td>
<td>131</td>
</tr>
<tr>
<td>26</td>
<td>Product distribution by demand location</td>
<td>132</td>
</tr>
<tr>
<td>27</td>
<td>Product distribution by biorefinery site for demand location n=1</td>
<td>132</td>
</tr>
<tr>
<td>28</td>
<td>Product distribution by biorefinery site for demand location n=2</td>
<td>133</td>
</tr>
<tr>
<td>29</td>
<td>Product distribution by biorefinery site for demand location n=3</td>
<td>133</td>
</tr>
</tbody>
</table>
LIST OF TABLES

Table 1: Decision Variables 56
Table 2: Parameters for Constraints 58
Table 3: Parameters for Objective Function 59
Table 4: Feedstock Processing Capacities 76
Table 5: Chemical Conversion Technology Coefficients 77
Table 6: Feedstock Decay Profile 78
Table 7: Biorefinery Capacity and Construction and Startup Costs 80
Table 8: Components of Feedstock Cost 82
Table 9: Components of Feedstock Cost – Metric Units 83
Table 10: Conversion & Operating Costs 84
Table 11: Planting and Harvest Seasons 86
Table 12: Feedstock Availability 88
Table 13: Feedstock Availability – Metric Units 88
Table 14: Farm Area Limits 89
Table 15: Base Demand Levels 92
Table 16: Base Revenue Levels 92
Table 17: Product Distribution Costs 94
Table 18: Trivial Validation Results 103
Table 19: Assumptions for Implementation Example 104
Table 20: Example Solution Validation Results 108
Table 21: Feedstock Transportation Distances 112
Table 22: Product Distribution Distances 112
Table 23: Dual Variable Examples for Processing Capacity 135
1.0 INTRODUCTION

1.1 Context

A major goal shared by public and private proponents of a U.S. biomass industry is the establishment of a large-scale ethanol manufacturing industry using non-food and residual biomass feedstocks. The Biomass Research and Development Act of 2000, in conjunction with the Clinton Administration’s August, 1999 executive order 13134 prompted the formation of the Interagency Biomass Research and Development Initiative. This initiative is a multi-agency collaboration headed by the U.S. Department of Energy and the U.S. Department of Agriculture whose mission is to “coordinate and accelerate all Federal biobased products and bioenergy research and development.” (Biomass Initiative, 2006) There are two governing bodies within the initiative, including a council of cabinet level officials from participating agencies, and an advisory committee of external experts from industry, academia, non-profits, agriculture, and forestry. The members of this committee have included representatives from industrial citizens such as Cargill, Archer Daniels Midland, DuPont, Dow, Southern Company, Weyerhaeuser, Deere & Company, and Genencor International. They have also been members of academic and non-profit institutions such as North Dakota State University, Cornell University, the National Corn Growers Association, the Illinois Corn Marketing Board, and Minneapolis-based community action group, Institute for Local Self Reliance. This broad spectrum of interested parties and stakeholders demonstrates the attention that biomass technology is receiving and indicates its increasing importance on the national agenda.
The Energy Policy Act of 2005, signed into law by George W. Bush, preserved and promoted various incentives dealing with market creation and production incentives. This includes a mandate for use of alternative fuels by government fleet vehicles when available, commercialization initiatives and incentives for hybrid flexible fuel vehicles, and tax credits for alternative fuel infrastructure development. It also preserves tax credits to ethanol producers. (Alternative Fuels Data Center, 2006) The Bush administration has further set a goal of “7.5 billion gallons of ethanol and biodiesel use by 2012” and seeks to “foster the breakthrough technologies needed to make cellulosic ethanol cost-competitive with corn-based ethanol by 2012.” (Whitehouse website, 2006)

A concrete example of federal action towards the advancement of biomass technology research and development is the U.S. Department of Energy’s National Renewable Energy Laboratory (NREL), which runs a major biomass research and development program. (NREL, 2006) The “Biomass Program” is coordinated by the National Bioenergy Center (NBC). The NBC consists of a number of applied research programs focused on 1) bioprocess pretreatment technologies, 2) molecular biology, 3) industrial thermochemical conversion technologies such as gasification, 4) analysis of novel biomass conversion processes, and 5) industrial design, integration, and commercialization of biomass technologies. This industrial design, integration, and commercialization program is responsible for partnering with industrial stakeholders such as DuPont and Deere & Company, who are working toward the establishment of a lignocellulosic biorefinery industry.

Biorefineries are facilities analogous to petroleum refineries, only the feedstocks are virgin or residual biomass materials. Interestingly, many of the biobased products and chemicals being developed are direct or indirect
substitutes for their petroleum analogs. The prime case is ethanol, which can be produced via fermentation of biologically available sugars. In the long term, biorefineries, like petroleum refineries, will derive value from being able to use a high mass fraction of their raw materials and converting them to a wide variety of products, thus maximizing revenue per unit resource. For now, the focus is on establishing a platform centered around ethanol using a small number of feedstocks, such as corn grain, corn stover, and in some cases straw and grasses. Lignocellulosic ethanol feedstocks for consideration in the long-term currently include woody plant matter, grasses, crop harvesting residues such as chaff and stover, municipal wastes, sawmill waste, paper making residues, and post-consumer paper waste. These materials differ chemically from corn grain, thus imposing different technology requirements. Inherent to most if not all of these materials are wide geographical dispersion, high variability in quality and composition, seasonality of supply, limitation in distribution infrastructure, and limitation in operational and economic data from an ethanol manufacturing perspective. The infrastructure limitations are of particular significance because there are few direct precedents for the large-scale harvesting, collection, transportation, storage, and logistical policies required for a lignocellulosic feedstock supply chain system. The operational and economic parameters involved in forecasting what a lignocellulosic biorefinery industry might look like are not difficult to conceive, but until an industry is up-and-running the validity of such parameters may be quite difficult to substantiate. This classic business case of “chicken-and-egg” is further complicated by the fact that venture capitalists are less likely to invest in an emerging industry when there are few proven commercial scale facilities to date.
These challenges place even greater importance on the development of a feedstock supply chain model to analyze and evaluate possible infrastructure configurations. To begin to define and examine the feedstock supply chain, the NBC’s Biomass Program sponsored a multi-authored “Roadmap for Agriculture Biomass Feedstock Supply in the United States.” (DOE, 2003) This roadmap identifies specific research needs in biomass supply infrastructure, including feedstock production, harvesting and collection, transportation, storage, preprocessing, and system integration. Among these recommended research areas, the system integration component lends itself directly to a problem solving approach based on systems engineering methodologies and mathematical optimization tools. A systems approach to feedstock supply chain challenges could potentially generate solutions that are holistic, robust, and practically feasible.

However, biorefinery development must also be considered from the demand side. The location and timing of product demand will play a major role in the decision processes that guide where biorefineries are sited, their capacities, and when and how much to produce. Ethanol demand will be driven by the dynamic gasoline market with its associated complexities of seasonality, environmental regulation, and refinery, terminal, and blending locations. Because ethanol cannot be transported in conventional petroleum pipelines due to physical characteristics, it must arrive at blend points via other logistical means. These other logistics channels, such as freight or rail, will be costly and important to manage. Thus integrated biorefineries will be at the interface of the transportation and logistics networks for two major commodity categories, agricultural materials and petroleum. Other biorefinery products may be of higher value than ethanol. These other products will likely be intermediate
chemicals that will serve as material supplies to specialty chemical or consumer products markets. This will introduce an even more complex distribution model into the scope of the demand side of biorefinery business models. Systems engineering and mathematical optimization will also serve as useful decision tools for this additional demand aspect of integrated biorefineries.

1.2 Background

One of the unique challenges of lignocellulosic biorefinery systems is the coordinated organization of feedstock collection, storage, and delivery infrastructures. These agricultural aspects of biorefinery systems ultimately impact end product distribution to customers, who are typically petroleum companies. Whereas supply chains are mature and well established for industries such as petroleum refining and the conventional corn based ethanol industry, coordinated supply chain systems of the magnitude and complexity required for commercial lignocellulosic ethanol are still in the early stages of development. This is a systems challenge with many aspects. These include necessary modifications in harvesting machinery, seasonality of feedstock availability, feedstock quality control, pre-processing methods, and inventory management for both feedstock and end product. However, the focus of this work is on feedstock supply policies and product distribution policies for a network of lignocellulosic biorefineries.

The term lignocellulosic refers to a material composition consisting primarily of long-chain carbohydrates and lignin. The long-chain carbohydrates are cellulose and hemicellulose, consisting of six and five carbon sugar monomers, respectively. In the biorefining process, these carbohydrates are chemically hydrolyzed to their component sugars, which are then
biologically fermented and purified to yield ethanol or other fermentation products. Lignin is a complex aromatic compound, often difficult to breakdown. While some co-product applications for lignin have been or are being developed, it is also common to use it as industrial boiler fuel.

Although the compositions of lignocellulosic materials do present specific biotechnology challenges to the biorefining process, they are beneficial in the sense that there are many low-cost feedstock alternatives that share very similar compositions. This means that biorefineries could potentially receive a number of different feedstock types, thus allowing for economic flexibility and risk aversion in the face of feedstock supply seasonality and price volatility. However, this adds significant complexity to decision making. For example, managers would need to decide

1) which feedstocks to purchase,
2) when, from where, and how much to purchase of each feedstock,
3) where, how much, and how long to store each feedstock, and
4) where, when, how many, and how big are biorefinery plants.

These considerations are only a few of many decisions to be made in coordinating a feedstock supply system, but answering these feedstock questions will make a major impact on all other biorefinery decisions. The quantities, timing, and locations of product demand also play major roles in biorefinery system decision making. This leads to an additional set of “demand side” questions:

5) how much of and when to produce each product,
6) how much of and where to distribute each product, and
7) how to plan for additional production capacity.

Questions one through seven are the motivation for this study.
1.2.1 Key Questions

**Question #1: Which feedstocks should be purchased?**

A biorefinery must consider which feedstocks it should procure. This decision is heavily influenced by conversion technology configuration, meaning that if a facility is designed for only one type of feedstock, then only that feedstock type can be procured. Alternatively, biorefineries that are capable of receiving various feedstock types have a more flexible, but more complex set of decisions in terms of supply. Thus any research effort that discusses feedstock procurement should consider approaches and methodologies appropriate to single or multiple potential feedstock types.

**Question #2: When, from where, and how much feedstock should be purchased?**

At any point in time, product demand for ethanol or other biorefinery products will affect their inventory levels, which in turn influence the production demands on the biorefinery. The production demands further impact the feedstock procurement demands. Thus feedstock supply management is crucial, making seasonality of feedstock availability an important consideration.

The place of origin of the feedstock is also key. Factors such as distance from farm to biorefinery, farm size and yield, and feedstock quality vary from one supply source to the next.

The amount of feedstock purchased at any given time from any given place will need to be considered as well. Feedstock purchased must become a function of demand volatility, product price, feedstock scarcity, feedstock price, and other factors including storage. Thus research efforts are needed in these areas.
**Question #3**: Where, how much, and how long to store each feedstock?

Because feedstock production levels are seasonal, storage durations may need to span multiple months if biorefineries operate outside of harvest seasons. The high bulk density of lignocellulosic feedstocks at harvest imposes large volume requirements on storage. The decision of where to store the materials thus depends on the economics of storage at the biorefinery versus storage on the farm or some intermediate location.

Feedstock storage levels decisions relate to the amount of feedstock purchased and the rate at which that purchased amount is consumed over time. The economics of feedstock storage for long durations may become more or less favorable depending on the price of feedstock, the cost of storage, rate of spoilage, and the price of end products. The cost of storing large quantities of materials over long durations must factor into production decisions.

**Question #4**: Where, when, how many, and how big are biorefineries?

The decision making model to construct a biorefinery is clearly complex and could incorporate many kinds of strategic business factors, some of which could not be easily quantified. These may include regulatory stipulations, access to employees, political sensitivity, long term competitive strategy, financial health, adversity to investment risk, and so on. The question as it pertains to the biorefinery supply chain system is limited to a more quantifiable scope.

The location of a biorefinery affects transportation costs of feedstocks and end products. A good location would presumably also be in a region where feedstock is plentiful, but only to the point where product distribution channels could be economically accessed. The time of construction is influenced by the growth in product demand / industry growth, which is generally expected to
grow significantly in the next few decades. The number of biorefineries in a specific area is an important decision because the density of supply and the locations of demand points imply that there is an economically favorable configuration. There should be enough biorefineries in a region to meet demand, but not so many that they are competing for the same feedstocks and driving up costs due to increased transportation distances. Similarly, the size of biorefineries is a key factor. Should they be large and centralized or smaller and more distributed? Like any facility, economy of scale is important, but so is balancing cost incurred by feedstock transportation and product distribution distances. As facility size increases and feedstock demand grows, the collection distance increases and incurs greater transportation costs per unit feedstock.

**Question #5: How much of and when to produce each product?**

Production levels of ethanol or other end products are influenced by product demand and price, but also by the factors described in all of the other questions. For example, product price and demand might be quite high at a particular demand location. But if, for a particular biorefinery, feedstock is scarce and prohibitively expensive to store, it may not be profitable to produce at all. In this case competing biorefineries would meet the product demand.

Production scheduling and inventory also come into play. Assuming a steady demand for product but a volatile cost of production, a biorefinery may choose to hold product inventory but not produce during times of expensive production in order to meet demand without incurring excessive cost.

**Question #6: How much of and where to distribute each product?**

A biorefinery should allocate its products among its customers over time so as to achieve the highest profit. Because product prices may vary by
location, and distribution costs will increase with distance, products should tend to be allocated to demand locations that offer higher prices and that are closer to the biorefinery.

**Question #7: How to plan for additional production capacity?**

As the biorefinery industry grows, it may become advantageous to add capacity to existing biorefineries. This decision is affected by demand, but also by feedstock availability and many of the other factors described above.

### 1.3 Literature Review

Researchers have been addressing some of the above system questions from the perspectives of agricultural engineering, agronomy, forestry, and chemical engineering. While useful, most of this research to date has focused on a particular component or detailed aspect of the entire system. Some of the studies discussed below do, however, seek to model and analyze more holistic systems. Even so, these approaches often leave out important global considerations, such as the integration of biorefining systems with petroleum supply systems. As these research papers are reviewed, their content will be discussed with respect to their modeling approach, data, analysis, and validation. But in order to evaluate how they address the complete biorefinery supply chain system, they will also be critiqued according to how they address the key questions from section 1.2.1.

Epplin (1996) developed a set of cost models for the production and delivery of switchgrass to a hypothetical ethanol facility in the southern plains states. This study established a set of feedstock supply operating parameters that were used to generate total system cost based on different yields, land lease rates, harvesting costs, and handling and transportation costs.
The author assumed an industry structure of vertical integration between feedstock production and ethanol processing. It was foreseen that the biorefinery operator would utilize feedstock supply contracting, land leasing, or purchase of supply through an organized cooperative in order to achieve better control of raw material procurement. It was assumed that the “vertically integrated” system would include harvesting crews and machinery, either managed directly by the biorefinery or contracted through a third party firm. Note that the land owner was not considered as the harvester. Although securing supply would be a key operating issue for the biorefinery, the author’s degree of vertical integration could be lessened to allow the possibility of more farmer control over feedstock supply and harvest. The biorefinery might choose to deal directly with large farmers or the cooperative, who might perform the harvesting functions themselves. Due to farmer freedom of participation, the centrally controlled workforce may or may not have access to all of the land needed to supply the biorefinery.

The author chose a single perennial crop, switchgrass, as a feedstock and assumed an extended harvest period from July through December, with off-season storage to level supply. To challenge this notion, instead of a single feedstock, a multi-feedstock biorefinery system might level supply in a number of ways.¹ Having multiple available feedstocks would diversify supply during harvest, allowing the operation to procure a mix of feedstocks over time at lowest cost. Multiple feedstocks could also be used to achieve a longer total harvest period. For example, wheat straw could be harvested in spring to complement switchgrass harvest. The authors state that the effects of storage

¹ Processing multiple feedstocks requires that the pretreatment and processing technologies are configured accordingly.
on feedstock quality and conversion yield due to decay require more research. On that point, a multi-feedstock approach might also lessen the need for lengthy storage periods, thus avoiding some of the feedstock storage costs and potential material decay.

It was assumed that continuous supply to the biorefinery at a constant rate would be necessary to meet production needs, and that harvest and storage would be scheduled to meet these needs. However, continuous production at a constant level would be unlikely. Like petroleum refineries, biorefinery production would likely be adjusted up and down over time as a function of product demand. This production would not be a function of product demand alone, but also dependent on the cost and availability of feedstock supply. Biorefineries should be assumed to produce at an optimal economic level considering both feedstock supply costs and product demand. Thus the feedstock supply profile and product mix will vary.

Epplin assumes that biorefineries are located at the transportation center of the feedstock production area. While this is a possible and likely outcome of biorefinery design, it should be noted that the product demand locations would be a factor in considering biorefinery location. This approach would consider feedstock supply and product demand together in the economics of the biorefinery.

Epplin’s consideration of land use requirements is simplistic and static. A constant feedstock processing level of 1800 dry metric tons per day of switchgrass was used, with a static land area requirement of 70,000 hectares within a static radius of 80 kilometers around the biorefinery. This approach suggests that little if any allowance is made for changes in feedstock production yields, switching between feedstocks, fluctuating product demand levels, or
variability in farmer participation rates. In reality, even if land leasing and harvest functions were a vertically integrated part of biorefineries (i.e. 100% participation), the changes in agronomic yields and product demand alone would cause the land requirements to vary over time. A multiple feedstock approach would also affect the actual land requirements and collection radius from the facility, since land requirements and availability would vary by feedstock type.

Epplin’s focus was on estimating the costs of switchgrass establishment and maintenance to support an ethanol production facility. In that regard, the methods employed were thorough, incorporating cost estimation software modules for capital and operating farm costs, as well as available research findings on switchgrass physiology, management, and harvesting practices. The total costs for delivered switchgrass were in the range of $33 to $44 per dry metric ton. The base case scenario considered a yield of 9 metric tons per hectare, land rents of $74 per hectare per year, and harvesting costs of $107 per hectare per year. The author also provides a sensitivity analysis for these figures, considering the impact of changes in yield, lease rates, maintenance costs, and transportation. More important than the author’s results, the assumptions for the modeling approach, data used, and analysis provide a potential comparison for parameters and approaches developed in the present study.

Epplin concludes by raising additional research recommendations. Among these are the need for economic research in comparing switchgrass to other feedstocks on a regional basis. He also suggests the need for additional work in determining optimal facility locations. These suggestions again assume a single feedstock approach, but to the author’s credit, he implies that the
interaction of costs for various feedstocks and facility locating play important roles in biorefinery systems design.

With respect to the key questions from above, Epplin’s work achieves the following.

1) *Which feedstocks to purchase?* – The author’s predisposition toward switchgrass as the single crop for his system stems from his desire to evaluate the economic viability of switchgrass production as a feedstock and not so much a desire to analyze biorefinery supply chains more broadly. Thus the choice was an assumption rather than the result of analysis.

2) *When, from where, and how much to purchase?* – While the data collection and infrastructure assumptions are detailed and thorough from a farm operation perspective, the approach around these aspects of modeling are made as rigid assumptions against which the author can evaluate switchgrass economics. Although there is a noteworthy sensitivity analysis around some of the parameters, the study was not intended to explore the dynamics of “When, where, and how much?”

3) *Where, how much, and how long to store?* – Simple assumptions are made and the author makes note of these questions as important additional research areas.

4) *When, how many, and how big are biorefineries?* – The study assumes a single biorefinery and uses a range of facility capacities in its calculations based on estimates from other sources. Timing of biorefinery construction is not discussed.

5) *How much of and when to produce each product?* – The author assumes production of ethanol only at a constant level year-round.
6) *How much of and where to distribute each product?* – This is not discussed.

7) *How to plan for additional capacity?* – This is not discussed.

Perlack and Turhollow (2003) conducted a similar study on corn stover as a feedstock to an ethanol production facility. They studied the economics of stover collection, transport, and storage as well as the factors affecting feedstock availability, such as yields and farmer participation rates. Using the data generated from this work, they analyzed the tradeoff between facility size and feedstock transportation distance. This was complemented by a further analysis of the economics of collection and transportation alternatives.

Like Epplin, the authors assume a single feedstock system with year-round operation at a constant production level. This implies a steady supply of stover and a non-volatile market demand for ethanol. As suggested earlier, this limits the scope of the analysis in that multi-feedstock flexibility is not considered. Furthermore, their delivered feedstock cost results are based on continuous supply for constant production levels rather than fluctuating ethanol demand patterns.

The raw data and assumptions built into their method of modeling feedstock availability are thorough. They incorporate corn yield, soil nutritional requirements, density of agricultural land use, participation rates, and physical accessibility restrictions. The corn yield figure is converted into a stover yield based on a 1:1 mass ratio of grain to dry stover. This permits the calculation of total stover yield. Of this total yield, only a certain portion should be removed because of the nutritional value of residual stover in the field, also considering effects of erosion. The authors suggest that as a base
figure, no more than 35% of stover should be removed from the field in order to maintain sufficient soil quality. From a biorefinery system perspective, the overall collection availability is also impacted by the agricultural land density\(^1\) within the landscape surrounding the biorefinery, since a higher agricultural density improves the transportation radius and feedstock economics. A further consideration is the percentage of farmers that wish to contract their stover supply. Competing uses for cellulose and the willingness to relinquish nutritional content contribute to the degree of farmer participation. Finally, the authors factor in the physical limitations of field access due to obstacles like flooded land, field slope, and equipment inefficiencies under prohibitive field conditions.

Although these availability assumptions contain the right elements, the authors take a static approach to the analysis. Their sensitivity analysis does consider the impact of variation in availability on delivered feedstock costs, but this does not get at the dynamic nature of availability or any of the factors included in the analysis. Such analyses would contribute to understanding the overall dynamic behavior of biorefinery supply chains and allow informed decisions in planning biorefinery systems with respect to feedstock supply assumptions.

Perlack and Turhollow also provide a simple method of calculating collection area based on feedstock requirements. This takes the annual feedstock requirement and divides by the stover availability to arrive at needed collection area. This can only be considered to be a rough estimate because the dynamics of feedstock requirements will cause the required collection distance to change constantly. In addition, if the biorefinery system were to include

\(^1\) Amount of land area used for agriculture as a portion of total land area.
more than one feedstock, all of the availability factors for the alternative feedstocks would also affect the collection distances for those crops. These considerations alone make the calculation of a necessary collection area much more complex than the authors assume.

Perlack and Turhollow also describe alternative collection, transport, and storage systems. The collection alternatives survey several combinations of harvest machinery as well as field to storage logistics. The authors present a useful set of cost curves based on this analysis. These curves display the sensitivity of feedstock costs as a function of biorefinery size for two different harvest-to-storage alternatives. However, the storage assumptions are again based on a constant ethanol production level and a single crop model, which limits the harvesting window and creates very large feedstock storage requirements for year-round ethanol production. The model includes a number of long-term storage sites located at field edges, which feed the smaller short-term storage at the biorefinery site. Although this two-tiered storage approach may be warranted, the design again ignores the possibilities presented by multiple feedstock approaches. Multiple feedstocks could mean larger overall harvesting windows which could decrease storage capacity requirements in the off-season. Feedstock flexibility may also allow greater responsiveness for ethanol production in response to volatility in market demand. Thus while the authors have considered many important system elements and provided useful data, the analysis could have been taken further to reflect more dynamic market requirements.

With respect to the key questions from above, Purlack and Turhollow achieve the following.
1) *Which feedstocks to purchase?* – The authors pre-select corn stover as the feedstock material since the chief goal of the study is to evaluate collection, handling, and hauling of stover.

2) *When, from where, and how much to purchase?* – Like the previous study, the authors assume a radial collection distance from a single facility and perform an economic sensitivity analysis with respect to this distance. The single harvest season is logically the time of purchase. The amount purchased is assumed to be equal to the annual capacity and based on continuous production at a constant level.

3) *Where, how much, and how long to store?* – The authors assume dispersed intermediate long-term storage sites, which accommodate the entire year’s capacity. These stored materials are drawn down at uniform levels concomitant with the feedstock needs. Thus the authors do not attempt to model the dynamic variability of this aspect of the system.

4) *When, how many, and how big are biorefineries?* – The study assumes a single biorefinery and uses a range of facility capacities in its calculations based on estimates from other sources. Timing of biorefinery construction is not discussed.

5) *How much of and when to produce each product?* – The authors assume production of ethanol occurs at a constant level year-round.

6) *How much of and where to distribute each product?* – This is not discussed.

7) *How to plan for additional capacity?* – This is not discussed.
Thorsell et. al. (2004) built on the previous Epplin study by considering a multiple feedstock collection system to feed a biorefinery. This work focused solely on collection economics and did not consider the economics of transportation or storage of the feedstock. Thus it was far from a complete system study. However, it did consider an important aspect of potential biorefinery system design in that multiple feedstocks are assumed to increase the length of the overall harvesting window. This assumption is based on multiple species having different harvest periods. Such an approach might allow lower feedstock inventory levels and costs. The authors suggest a conversion technology platform of feedstock gasification into synthesis gas which then undergoes anaerobic fermentation. They further suggest that this process has the potential to permit a wide range of lignocellulosic materials as feedstocks for the biorefinery. These design assumptions support a biorefinery system model that might be more responsive to changes in delivered feedstock prices and allow the operation to change out one feedstock for another on short notice.

The outcome of the Thorsell et. al. study is a thorough feedstock collection cost analysis. It includes the costs of specialized labor crews and harvesting equipment for harvesting switchgrass, native prairie grasses, and wheat straw. Cost sensitivities to crop yield and biorefinery capacity are included.

The authors again assume a steady supply of feedstock to the biorefinery. The analysis is non-dynamic in that they do not consider changes in feedstock requirements or ethanol demand over time. Unlike Perlack and Turhollow, Thorsell et. al. do not consider any availability multipliers for these feedstock species since it is assumed that the root systems remaining after
harvest are sufficient to maintain soil nutrition. Furthermore, they assume that all of the straw and grasses will be available to the biorefinery system, implying 100% farmer participation.

With respect to the key questions from above, Thorsell et. al. achieve the following.

1) *Which feedstocks to purchase?* – The author does consider multiple feedstock types, including corn stover, wheat straw, switchgrass, wood residues, and various other types of grasses. However, the study was not intended to address procurement decisions from a biorefinery perspective. Thus it is not a complete system evaluation.

2) *When, from where, and how much to purchase?* – Although the study does not directly address these questions, their study does imply a migratory harvesting approach, where in the case of wheat straw, dedicated harvesting crews begin in Texas during May and travel north to Canada over the summer months. Similar approaches are discussed for other feedstock types.

3) *Where, how much, and how long to store?* – Discussion of storage is limited to field edge storage and does not include intermediate storage or storage at the production site.

4) *When, how many, and how big are biorefineries?* – Although this is not analyzed or specifically discussed, the authors seem to assume that harvesting crews serve multiple biorefineries.

5) *How much of and when to produce each product?* – This is not discussed.

6) *How much of and where to distribute each product?* – This is not discussed.
7) **How to plan for additional capacity?** – This is not discussed.

Nilsson (1999) developed a set of related sub-models simulating a straw harvest and delivery operation for combustion at a central heating plant. Discrete event simulation (DES) modeling was used to describe most of these sub-models. The locating DES sub-model facilitated the evaluation of alternatives for locating the central facility and feedstock storage sites. The weather and field drying DES sub-model simulated the dynamics of feedstock moisture content and drying. Output from this sub-model could be used as information for harvest decisions. DES was also used to model the dynamic availability of feedstock resulting from mechanical harvest. The output from these sub-models could then be used as inputs to a static spreadsheet sub-model that calculated the monetary costs and energy requirements for the harvesting and delivery operation.

The locating sub-model was designed to evaluate alternative facility and storage sites. In order to test alternatives, facility sites were simulated in the locating sub-model according to probability distributions representing the size and yield of each of the field areas within the regional landscape surrounding the facility site. In this way, the author designed a tool to simulate probabilistic land availability for feedstock production.

The harvesting and handling sub-model simulated the harvest start dates as triangularly distributed random variables. “Arrivals” of completed harvest operations were modeled using a Poisson process which also incorporated rainfall modeling information. If the fields were too wet, the corresponding Poisson arrivals were not used. Feedstock yield per unit land area was modeled
as a normally distributed random variable. Once arrivals occurred, the feedstock was assumed to be left in the field for drying.

The weather and field drying sub-model simulated the dynamics of moisture content of mechanically combined feedstock in the field using empirically derived differential equations for physiological and weather related moisture. Moisture data taken for the chosen facility location would then provide values of parameters for the equations. These equations could then be used to supply time dependent moisture state variables for the DES. Moisture content information would allow decision makers to know when to collect feedstock from the fields.

Mechanical feedstock collection was simulated using deterministic equipment capacities along with probabilistic treatment of mechanical failure and repair. This part of the model determined the time required to collect the feedstock.

The collective output data from these DES sub-models would allow the calculation of energy use and monetary costs for harvesting, collection, and transport to a heating facility. This was done using a static spreadsheet model that considered the cost of feedstock, capital investments, labor, and operations and maintenance.

Nilsson (1999) continued this work in a follow-up publication with specific examples of how his DES sub-models could be used to analyze real alternatives for a straw collection and harvest system. The author modeled three alternative locations in Sweden that exhibited different regional landscapes and weather patterns. Using the simulation sub-models, it was shown that overall system costs varied among the three alternative locations. Each location exhibited different harvesting efficiencies and costs due to
weather, relative distances to facilities, and feedstock density and availability. The author also showed the effects of changing key management assumptions, such as increasing the number of permissible straw varieties harvested. Also considered were increasing the allowable moisture content for collection and increasing the number of remote storage locations. These types of assumptions were easily tested using DES and each returned improved system performance. Finally, the author investigated the sensitivity of system costs to changes in equipment and labor configurations. For example, an increase in the number and capacity of straw balers used increased average annual harvest amounts while decreasing the average cost per baled tonne of straw.

The discrete event simulation approach taken by Nilsson was a more sophisticated way of modeling harvesting practices and costs than were the approaches of previously mentioned authors. Since Nilsson captured the dynamic and probabilistic nature of weather, yield, and machinery failure in conjunction with the impact of alternate regional landscapes, the output data generated is more robust. Similarly, the sensitivity analyses performed go beyond the static approaches of other authors. Applying the sub-models to multiple real-world system alternatives demonstrates the analytical power of the DES modeling approach.

Although probabilistic modeling of landscapes may not be exact enough for a detailed design, this tool would be well suited to feasibility studies and preliminary system designs. Unlike Perlack and Turhollow, Nilsson has not given much consideration to the participation rate of contracted farmers. This may be because Nilsson assumes that a Swedish system would be totally integrated from a management perspective.
While Nilsson carried out an excellent study, the scope is limited from the perspective of a total biorefinery system model. It only addresses the operation from field to feedstock transportation. While Nilsson’s intent for the collected feedstock was strictly combustion in a heating plant, the biorefinery research community may have also benefited if Nilsson had addressed final product demand issues. These might include where and how the steam would be used, what the seasonal steam demand patterns might be, and how to incorporate the costs of steam distribution with the costs of feedstock harvest and collection. Only with this expanded scope would the modeling effort be a complete systems picture.

With respect to the key questions from above, Nilsson’s studies achieve the following.

1) *Which feedstocks to purchase?* – The author limits the modeling to straw as a combustion fuel for a heating plant. Thus the study does not directly apply to biorefineries.

2) *When, from where, and how much feedstock to purchase?* – Although a great deal of statistical rigor was exercised in modeling the agricultural and climactic dynamics of the collection and handling system, the author only briefly addresses the actual feedstock demands from the perspective of the heating plant, and this is done in a more deterministic way. This is puzzling, since it would seem that many of the submodels, especially the locating and harvesting submodels, would be somewhat dependent on the magnitude of the feedstock demand.

3) *Where, how much, and how long to store?* – The author’s approach to this question is more rigorous than that of previously discussed studies. The DES locating submodel is used to determine the most probable
locations of storage facilities and the heating plant based on random variables whose distributions represent the potential density of straw, the locations of farms, and the size of farm fields. This differs from other studies, whose treatment of these parameters assumes deterministic ranges or single values.

4) *When, how many, and how big are biorefineries?* – The study only considers a single heating plant and does not discuss time of construction. Facility size is a configurable parameter, meaning that it can be set to whatever value is desired for analysis.

5) *How much of and when to produce each product?* – The author uses energy requirements profiles from other sources as input to the model rather than values to be determined.

6) *How much of and where to distribute each product?* – This is not applicable.

7) *How to plan for additional capacity?* – This is not discussed.

Grado and Strauss (1993) developed a set of inventory control models for supplying woody biomass (poplar) to an ethanol production facility. This model incorporated inventory systems that were linked together in a supply chain. The linked inventory models were the “storage” of standing trees at the plantation, storage of delivered chipped wood feedstock, and tank storage of end-product ethanol. Thus the scope of the analysis also included the ethanol manufacture. A secondary objective of this work was to apply the inventory models to five different tree planting rotation schedules to determine an optimal harvesting policy for each rotation length.
The plantation inventory model was comprised of a set of technical and cost parameters. The technical parameters defined the type of biomass to be used, the size of the plantation, the tree spacing, and the rotation schedule. The costs included establishment costs, such as soil preparation, planting and fertilizing. They also included post-establishment maintenance costs such as pest control, land rent, labor, and management.

The harvesting and storage inventory model technical parameters defined the harvesting methods, transportation methods and distances, and storage methods. The cost parameters for harvest and storage included the costs of cutting and chipping, transportation, and final movement of chips from storage to processing.

The manufacturing and end product storage inventory model included parameters that defined the ethanol production method (hydrolysis and subsequent fermentation), the quality of the feedstock, the material conversion rate, the facility capacity, and the annual demand rate. The cost parameters for the manufacturing and end product storage inventory model include processing costs and ethanol storage costs, with no credits for co-products.

The optimization approach sought to find the least cost ethanol production cost among the possible harvesting policies for each rotation length. The optimization method employed was dynamic programming with deterministic demand parameters. The authors assume a certain annual demand and suggest that monthly demand can vary according to the monthly demand for gasoline. This correlation to gasoline was based on their analysis of historical data. Their treatment of end product demand rate is of key importance because it links the dynamic harvest of feedstock to the dynamic demand for end-product in a single approach. The authors also assume
unlimited ethanol storage capacity and a considerable lag between feedstock harvest and end product demand. For instance, an October biomass harvest would correspond to December ethanol and gasoline demand.

Although the authors’ dynamic treatment of feedstock and end product demand is another commendable step forward in biomass supply chain modeling sophistication, they do not carry this through to the extent of modeling the distribution of the end product to the demand location. This missing element would also influence the economics of optimal harvest and low cost ethanol production in that the distance from ethanol storage to the point of blending with gasoline implies certain variable and fixed cost outcomes for ethanol transportation.

The unlimited ethanol storage capacity also fails to capture the realities of liquid chemical storage. The authors rely on their sources who make few if any claims regarding end product storage. Thus they apply a flat monthly carrying cost without fully considering the effect of unlimited storage capacity on carrying cost.

The authors determine minimum cost harvest policies for each of their rotation schedules of four, five, six, seven, and eight years. They contrast these with the maximum cost polices for each rotation length as a type of sensitivity analysis to arrive at a set of ranges for cost per liter of manufactured ethanol using their wood biomass based ethanol production system. While the study was a significant undertaking, they admit that further sensitivity analyses are needed to better understand the impact of plantation or manufacturing assumptions. To that effect, the sensitivity of the cost to various demand patterns is also needed. Although the authors make it clear that their model is
capable of representing fluctuating ethanol demand, they do not seem to focus on this aspect of the system, nor address how it would impact their results.

With respect to the key questions from above, this study achieves the following.

1) *Which feedstocks to purchase?* – This study considers virgin wood materials only.

2) *When, from where, and how much feedstock to purchase?* – The authors’ treatment of “when to purchase” and “how much” utilizes dynamic programming (a type of mathematical programming) as a procurement scheduling method. This is a departure from other studies and a key strength of this work. Many modern strategies for large scale procurement and production at manufacturing facilities utilize mathematical programming. This means that systematic algorithms are used to optimize the decision with cost minimization (or profit maximization) in mind. The results of using this method are tangible and specific output that guide a procurement decision for the biorefinery. Unfortunately, the authors’ consideration of “from where” is highly simplistic in that they use a single tree plantation. This eliminates the necessary rigor around feedstock transportation and biorefinery location from the analysis.

3) *Where, how much, and how long to store?* – The system was modeled using a “multi-echelon” inventory approach, meaning that the plantation, feedstock storage area, and final product storage were treated as three separate but linked inventory models. This means that feedstock was stored as trees pre-harvest, and as woodchip piles pre-conversion. The average amount of feedstock stored per period (where periods are
measured in years) varied according to the different rotation scenarios. When the rotation length increased, so did the average amount, cost, and storage duration of stored material. The details of this part of the analysis were not given. The “where” aspect of this question was not really considered since the plantation and facility locations were predetermined.

4) *When, how many, and how big are biorefineries?* – The study only considers a single biorefinery and does not discuss construction timing or capacity beyond making a static capacity assumption.

5) *How much of and when to produce each product?* – Since the authors were most interested in optimizing the harvesting schedule, this was not part of the analysis. This implies that the study only addresses a portion of the more holistic biorefinery supply system. Constant and continuous production levels are implied by asserting annual feedstock consumption.

6) *How much of and where to distribute each product?* – This is not discussed.

7) *How to plan for additional capacity?* – This is not discussed.

Grado and Strauss (1995) built on their previous work by applying their approach to alternate configurations using other or multiple feedstocks. They compare woody biomass versus “corn only” and a wood / corn combination. They conclude that the woody biomass system is the least cost method for ethanol production. However, they concede that real woody biomass based systems are not prevalent enough to provide actual proof of this conclusion. As with the previous study, this paper does not fully explore sensitivity analyses of
parameters or demand patterns in great detail, nor does it consider end product distribution.

With respect to the key questions from above, this study varies from the previous study in that multiple feedstocks are considered. The work essentially compares the system costs of different feedstock type configuration scenarios instead of comparing different harvest rotation scenarios.

Grado and Chandra (1998) carried out the sensitivity analyses to accompany the studies done using the inventory control and dynamic programming approach begun by Grado and Strauss. The authors applied a factorial design approach for testing the interactions of varying multiple parameters. In one experiment, the effects of three parameters were tested. These were feedstock deterioration, ethanol manufacturing capacity, and the market cost of feedstock procured from outside the system. They discovered that low deterioration and low outside feedstock cost resulted in the lowest cost solution. In a second experiment they tested the effects of plantation yield, harvest capacity, feedstock deterioration, manufacturing capacity, and material conversion efficiency. Their results showed that a smaller manufacturing capacity and favorable values for each of the other parameters exhibited the lowest cost solution.

This publication was a good complement to the previous Grado and Strauss studies, but still did not explore the impact that alternate end-product demand patterns might have on the cost of solutions. Additionally, there was still no treatment of end product distribution costs. These issues prevented the authors from fully incorporating the key components of a biorefinery system model.
With respect to the key questions from above, this varies from the previous study only in that operational parameters are changed as part of a sensitivity analysis in recognition that there are many factors at work. The study suggests that different biorefinery sizes (Question 4), material decay during storage, (Question 3), and feedstock price (Questions 1 and 2) have an impact on optimal supply schedules. Ethanol yield during conversion (Question 5), harvesting equipment efficiency (Questions 1 and 2), and plantation yield (Questions 1 and 2) also have an effect. This is a more mature system view than most of the other studies. However, these aspects of the system are considered as predetermined input parameters as opposed to values determined from analysis.

Nguyen and Prince (1996) developed an analytic method for sizing an ethanol plant by considering the parameters for the biomass resource base around the facility site. Their approach utilized a calculus model for a circular agricultural region. This led to an analytical solution such that optimal plant size occurs when the ratio of the exponent cost scaling factor for the ethanol production plant to the factor for transportation infrastructure is at a certain value. The authors also assess the benefits of using multiple feedstocks. In the case of Australian ethanol production from sugar cane, they claim that the benefits of extending the harvest period with sweet sorghum are significant. This is based on the idea that ethanol production only occurs while crops are being actively harvested, i.e. no long-term off season storage. Under this assumption, the capital costs of processing can be decreased because a longer harvest season implies a decrease in needed daily processing capacity to meet an annual demand rate. This is quite different from the prevailing assumption
in the United States, where feedstock would be stored in the off-season to smooth out production over the course of a year.

Although the facility sizing approach is not invalid, it is static. It assumes a given set of parameters for yield, fraction of useful land, transportation cost, and road winding factor. It also assumes a constant annual product demand. A facility sizing approach would be much more robust with an approach more similar to that of Nilsson’s discrete event simulations. Such an approach would model these parameters in a more dynamic fashion. As with some of the other studies already discussed, Nguyen and Prince consider neither the dynamic nature of the ethanol demand, nor the downstream distribution of final product demand.

With respect to the key questions from above, this study achieves the following.

1) *Which feedstocks to purchase?* – This study considers multiple feedstocks as an important factor in optimizing biorefinery size because it prolongs the harvest window and reduces needed capacity. It also implies that feedstocks are purchased when they are in season, and that these seasons do not overlap.

2) *When, from where, and how much feedstock to purchase?* – The “when” question is partly addressed with the authors’ treatment of Question 1. The “where” is implied to be from within the determined collection radius of the facility while the “how much” is assumed as an input parameter and not modeled as a result of analysis.

3) *Where, how much, and how long to store?* – The system in the authors’ model does not include long term feedstock storage but rather produces
ethanol immediately upon harvest. Thus there is no consideration of this.

4) *When, how many, and how big are biorefineries?* – The objective of the study is to establish a biorefinery sizing model, but this is only done at a very high level approximation based on simplistic static parameters.

5) *How much of and when to produce each product?* – The system produces to a preset annual demand and produces only during the harvest seasons.

6) *How much of and where to distribute each product?* – This is not discussed.

7) *How to plan for additional capacity?* – This is not discussed.

Jenkins (1997) has also developed an optimal scaling technique for facilities using biomass feedstocks. He also uses an analytical approach to explore the design scaling parameters used to determine optimal facility size. The work includes sensitivity analyses on these parameters. The author suggests that for large facilities, scale may not be as important as factors such as traffic loading, environmental considerations, or other siting considerations. This is based on his finding that after exceeding a certain minimal size, production cost is relatively insensitive to facility scale. The author concludes by mentioning that scale parameter data are lacking for very large facility sizes and suggests the need for additional case specific research.

With respect to the key questions from above, this study achieves the following.

1) *Which feedstocks to purchase?* – This is not discussed.
2) *When, from where, and how much feedstock to purchase?* – The study
does not specifically address these decisions, but like other studies the
author uses an “average collection distance” to define “from where” the
feedstock is purchased. Since uniform production levels are assumed,
the “how much” to purchase is implicitly “enough” to supply an entire
year. This is simplistic.

3) *Where, how much, and how long to store?* – This is not discussed.

4) *When, how many, and how big are biorefineries?* – The focus of the
work is on biorefinery size, and the author suggests a critical minimum
scale. Once above this minimum, the author concludes that size is not as
important as other regional factors.

5) *How much of and when to produce each product?* – Although this is not
thoroughly explored, the author assumes a uniform production level
throughout the year.

6) *How much of and where to distribute each product?* – This is not
discussed.

7) *How to plan for additional capacity?* – This is not discussed.

Aden et.al. (2002) at NREL published a comprehensive technical design
for a lignocellulosic biomass to ethanol processing facility based on enzymatic
hydrolysis and fermentation technology. This study was a rigorous chemical
engineering design considering the unit operations and project economics for a
prototype plant. The design components included feedstock storage and
handling, pretreatment and hydrolyzate conditioning, saccharification and co-
fermentation, enzyme preparation, and separation, distillation and water
recovery. Auxiliary components include wastewater treatment, chemical storage, and a combustion boiler.

The study provided many useful parameters related to the conversion operation, and there is a discussion regarding the biomass supply chain. This part of their design describes the process and equipment for feedstock storage and handling in detail. However, the operation is described as having a constant feed rate year round. The design includes remote long-term storage of feedstock sufficient to supply an entire year, and a separate short-term storage facility for three days worth of feedstock. Handling machinery is described from the point of receipt of feedstock through the mechanical processing of the feedstock.

The Aden et. al. analysis of the effects of plant size on collection distance is a simple calculation based on deterministic assumptions, including constant annual ethanol demand and static feedstock availability. Their delivered feedstock cost assumptions are also held constant. Furthermore, their long-term feedstock storage analysis is based on a constant demand for feedstock. Finally, there is scarce mention of how or where the ethanol is distributed or who or how large the customers would be.

With respect to the key questions from above, this study achieves the following.

1) *Which feedstocks to purchase?* – This is pre-assumed to be corn stover.

2) *When, from where, and how much feedstock to purchase?* – The authors design the operation assuming the receipt of a year’s supply of feedstock at harvest time from the region surrounding the facility. This region is defined by having an “average collection distance”. This is built into the design rather than being an output of their analysis.
3) *Where, how much, and how long to store?* – As mentioned above, the authors assume a remote storage site for year-round storage of a year’s supply of feedstock.

4) *When, how many, and how big are biorefineries?* – Biorefinery size is discussed with respect to collection distance, stover cost, and facility economies of scale. The conclusion is that after a certain critical minimum plant size, the economies of scale are balanced by increasing stover costs. The cheaper or more available the stover, the larger the plant can be while still achieving this balance. Sensitivity analyses are given on this topic. Time of biorefinery construction is not discussed, but their economic assumptions are based on construction after several other similar plants have been developed, established, and economically proven.

5) *How much of and when to produce each product?* – The authors assume a uniform production level throughout the year.

6) *How much of and where to distribute each product?* – This is not discussed.

7) *How to plan for additional capacity?* – This is not discussed.

Sokhansanj (2006) recognized the need for advancement in the area of biomass supply chain modeling and has overseen the development of a robust modeling framework to develop operating parameters such as cost per ton of delivered feedstock, energy input per ton delivered, and carbon emissions per ton delivered. The modeling system, IBSAL (Integrated Supply Analysis & Logistics), is the combination of several independent simulation modules. Each module simulates an operation in the biomass supply chain from harvesting to delivery. The modules collectively simulate the dynamics of:
• Timing of harvest
• Moisture content
• Agricultural yield
• Effect of weather on operations
• Equipment performance
• Transportation & handling
• Loss of dry matter

This is very similar to the approach taken by Nilsson, except that the modules are more specific to the lignocellulosic biorefinery and focused on three key parameters mentioned above. IBSAL is an evolving framework to which new operational modules continue to be added, thus increasing the scope and sophistication of the methodology for determining the parameters mentioned.

While the IBSAL modeling framework does not directly support decisions related to the seven key questions, it does provide a method for determining parameters to feed such decisions. With respect to the key questions, this study achieves the following.

1) *Which feedstocks to purchase?* – The study does not preclude any particular feedstocks and assumes any type of field harvested lignocellulosic feedstock.

2) *When, from where, and how much feedstock to purchase?* – This is not addressed.

3) *Where, how much, and how long to store?* – “Where” and “how much” are not addressed. Storage modules have not been developed for IBSAL, except that material decay is simulated.

4) *When, how many, and how big are biorefineries?* – This is not discussed.
5) *How much of and when to produce each product?* – This is not discussed.

6) *How much of and where to distribute each product?* – This is not discussed.

7) *How to plan for additional capacity?* – This is not discussed.

An important area of study in biomass supply chain systems is life cycle analysis. This type of analysis is high level systems engineering, usually with a focus on material availability, energy use, and environmental impact. The following life-cycle studies do not have a direct bearing on the project economics of a biorefinery supply chain system, and thus they will not be critiqued according to the seven key questions above. However, the information produced from such studies might aid decision makers in considering the long term impacts and social costs of their operations. Conversely, the data generated from biorefinery supply chain models can be used to supply design assumptions or data inputs for life cycle analyses.

For example, Börjesson (1996) has examined the energy efficiency and net fossil fuel displacement of biomass production and transportation in Sweden. The focus is on energy output to input ratios and efficiency of transportation distances for specific crop types by mode of transportation. While analyses such as this are always open to debate over data and assumptions used, this particular work does offer a life cycle interpretation of feedstock collection distance that can be used to validate biorefinery collection systems based on net energy balances.

Lynd (1990) examined lignocellulosic ethanol production from an interdisciplinary perspective focusing on net energy balances, sustainability of
ethanol as a transportation fuel, air quality impacts, raw material supply assessment, and the sensitivities of future production costs based on possible advances in technology. He cites a number of studies that estimate the energy required for lignocellulosic ethanol production to be a relatively small fraction of the energy content of the ethanol produced, on the order of 15%. He estimates current raw material availability as five quadrillion Btu in equivalent ethanol and assumes that this level is attainable with additional conversion technology development. Lynd also claims that if Conservation Reserve Program (CRP) lands were used at 1996 productivity levels, ethanol produced from biomass on those lands alone would approximately meet or exceed the energy needs of U.S. gasoline consumption. These are the most pertinent life cycle conclusions among several other high level statements in Lynd’s study.

More recent work by Lynd and Wyman et. al. (2005) consisted of a two-part study focusing on the benefits of diversifying the product slate at biorefineries to include high value co-products. The first part was a review of industries that are analogous to biorefineries, including petroleum refining and corn wet milling. Both industries developed additional production capabilities gradually, due to technology advances or new market demands. The second part was an analysis of the process economics at biorefineries and how these economics improve when additional co-products are produced. Products such as succinic acid, lactic acid, butanol, and others were used in the analysis. The economic viability of ethanol and each of these co-products was explained to be enhanced as the number of products increased within reasonable technology and market assumptions, both near and long-term.

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1 This would require a combination of currently idle CRP land and currently idle potential CRP lands, consisting of both grasses and forest materials.
McLaughlin et. al. (2002) studied the projected economic benefits to agriculture and estimated the environmental benefits of greenhouse gas emissions reductions through use of switchgrass for renewable energy. The authors claim that the introduction of switchgrass would increase overall farm profits by tightening the supply of other conventional crops while introducing switchgrass as a new crop into the mix. This is estimated to be a $6 billion increase. They suggest that the potential for direct and indirect economic benefits of switchgrass as a biomass fuel for ethanol and power warrant a modest subsidy to increase market demand and establish the maturing industry. In addition, the environmental benefits in the form of greenhouse gas reductions are significant, quoting an annual savings of 159 million metric tons.

McLaughlin et. al. make an interesting point in that much of the data available for life cycle analyses is engineering based rather than comprehensively operational, i.e. a total systems perspective. This implies that more research in biomass supply chain systems would provide a more complete basis for life cycle comparisons, both economically and ecologically. This would also promote a standardization of the assumptions used in life cycle and net energy balance studies, which are often difficult to compare due to inconsistent system assumptions.

In a different study, McLaughlin et. al. (2005) also conducted a comprehensive agronomic survey of prairie grass cultivation research for different varieties. This survey focused on breeding practices, crop production costs, soil sustainability, and optimization of crop quality for bioenergy production. The authors comment that while federal biomass program funding has begun to shift towards end market development and away from basic
agronomic research, the biomass industry must advance on all fronts simultaneously because of the importance of a total systems perspective.

The Biomass Research and Development Initiative sponsored a study on the feasibility of providing a billion tons per year of biomass to industrial consumers. This study, authored by Oak Ridge National Laboratory and the USDA (2005), is focused primarily on assessment of the biomass resource base and less so on the downstream logistical and technological processes for the development of the biomass conversion industry. The authors quantify the potential for feedstock supply based on an aggressive set of assumptions such as improved yields and harvesting efficiencies. Whether or not their assessment is accurate, the order of magnitude of their estimate implies that biomass use has the potential to displace as much as 30% of U.S. petroleum consumption. Even if only a small portion of this figure is ever achieved, it still suggests that a major biomass industry infrastructure would be required. This again emphasizes the need for a total systems approach to a biomass supply chain.

Pimentel and Patzek (2005) have reviewed the net costs and net energy balances for corn based and lignocellulosic ethanol production, as well as the costs and energy balances for soy and sunflower based biodiesel production. In all cases, they claim that net energy balances are unfavorable and that the financial costs of production outweigh the unsubsidized market value of these fuels. These findings are based on a set of system design assumptions that the authors validate by citing other studies using similar assumptions. They also seek to refute similar studies\(^1\) that report positive net energy balances by noting that their design assumptions are invalid. It is clear that the major issue in accurately assessing these life-cycle issues is a consistent framework upon

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\(^1\) Such as Shapouri, et. al. (2002) and Shapouri et. al. (2004).
which to perform the analyses. This again underscores the need for a comprehensive and robust approach to the overall biorefinery system from field to end consumer.

Although Pimentel and Patzek do recognize the potential economic benefits of fermentation co-products by including co-product credits in their analysis where appropriate, this does not adequately reflect the desired future state of the biorefinery industry. Even if their findings are accurate, as the industry matures, other more high value biorefinery products may tip the economic balance. Finally, if economically accessible petroleum becomes scarce enough over time, biomass may be the only sustainable source of commercial organic chemicals. In this scenario, it would no longer be a question of food versus fuel or net energy balances, but rather an imperative to be met with further biorefinery innovation and technology improvement.

Farrell et. al. (2006) conduct a survey of ethanol production net energy balance studies to assess the range of findings in both net energy contribution and greenhouse gas emission impacts. Their approach involves applying consistent system boundaries and co-product credits to all studies surveyed and comparing the results of net energy and greenhouse gas emissions. The adjusted results from the studies range Pimentel and Patzek (2005), whose adjusted results remain energy negative, to Shapouri, et. al. (2003), whose results remain positive. The remaining differences after adjustment can be attributed to different parameter values and assumptions. Farrell et. al. (2006) note that in the cases of negative net energy studies, the parameters and assumptions used are based on sources that are often outdated or poorly documented.
Greenhouse gas emissions are also assessed in Farrell et. al. (2006). These findings show the Pimentel and Patzek (2005) work to result in more net greenhouse gas emissions than do the results of Shapouri et. al. (2003). Farrell et. al. (2006) also include a progressive technology case where switchgrass conversion technology provides a net greenhouse gas emissions value that is nearly an order of magnitude below the Pimentel and Patzek (2005) results.

Morris (2005) enters the debate by explicitly critiquing the Pimentel and Patzek study. He claims that authors such as Pimentel and Patzek continue to bog down biorefinery research with endless and obstinate analysis to disprove beyond doubt that ethanol production has a favorable energy balance. Morris goes on to explain how as of 2005 this is completely unfounded. He compares all Pimentel and Patzek work to other net energy studies and contends that after years of renewed rigor, they still make assumptions that are sometimes incorrect and commonly out of line with their peers. What’s more, Morris holds that this has only served to distract and confuse public opinion, wasting valuable research potential on what could have been more constructively used for other important biomass research. The following excerpt demonstrates his position.

“Unfortunately, this small piece of the puzzle has tended to dominate the discussion of biofuels. In the process, important issues like the ownership structure of a carbohydrate economy or its implications for world trade and rural development have largely been ignored. It often seems that every article, every interview, every public discussion about ethanol starts and sometimes ends with the question ‘Doesn’t it take more energy to make ethanol than is contained in the ethanol?’ In 2005, the answer is clearly no. Yet the question will not go away. One might argue that this is because credible studies by one
or two scientists continue to keep alive the claim that biofuels are net energy losers… Another frustration is that the net energy discussion looks backwards, not forwards… Instead of [using the latest information] the studies reflect [data that can be as old as] 20 years old. This is not helpful to long range planning.”

An assessment of this collective body of literature reveals that several key system components and modeling considerations for a total systems approach have been considered, but never fully integrated into one study. The studies by Epplin (1996), Perlack and Turhollow (2003), Thorsell et. al. (2004), Nilsson (1999), Grado and Strauss (1993, 1995), Grado and Chandra (1998), and Sokhansanj (2006) touch on these. While all authors include the harvest and collection component, a smaller number include the transportation component. An even smaller number consider the production of and demand for final products. None discuss the distribution of final products, which is an important aspect of the overall economics of a biorefinery supply chain.

This body of literature also reveals that some important modeling considerations are taken into account, but again, are never fully integrated into one study. From a feedstock collection perspective, Sonkhansanj (2006) stands out as having the most robust approach, where the system is considered in a manner that is both probabilistic and dynamic. This is in contrast to the other authors, who use deterministic or static parameters in their work. However, this analysis ends with the delivery of the feedstock and does not consider final product distribution. From a modeling approach perspective, only Grado and Strauss (1993, 1995) and Grado and Chandra (1998) consider the dynamic behavior of ethanol demand, but this is not thoroughly explored in their work. In most of the studies, the authors assume that a constant supply of feedstock to the point of processing will be necessary, even though some recognize the
volatility of demand patterns. As Lynd et. al. (1990) point out, it is unlikely that production would actually remain at a constant level year round. Thus a modeling framework should allow flexibility of feedstock supply quantity and production of ethanol and co-products.

Some authors consider multiple feedstocks as a way to reduce inventories and reduce economic risk while others assume only a single crop system. Although multiple feedstock types at a single facility does present handling and pretreatment challenges, a biorefinery modeling framework should, at a minimum, allow and consider the option of multiple feedstock use. This diversification would help to reduce economic risks associated with feedstock supplies and prices.

Economic feedstock collection distance and facility size are studied as exclusive topics in some of the above studies, but are also discussed as part of the biorefinery design by Aden et. al. (2002). Nyguen and Prince (1996), Jenkins (1997), and Aden et. al. each approach the subject from a deterministic, static perspective accompanied by sensitivity analyses. It would be preferable to design a framework that permitted variable collection distance and determined facility size based on dynamic feedstock supply and product demand data. This would capture the trends and relationships between feedstock supply and final product demand in a more observational and dynamic way, rather than through predetermined system designs based on uniformly constant supply and demand assumptions.

Grado and Strauss (1993, 1995) designed a modeling framework built around mathematical programming that enables optimization of a portion of a biorefinery supply chain. Their model optimizes harvesting schedules for a single tree plantation for processing at an ethanol production facility using a
series of dynamic inventory control models. While this work is an important step in establishing a biorefinery modeling framework, their scope has limitations. The supply relationship between the plantation and the ethanol production facility implies a closed system. It is assumed that no other facility would use the feedstock from the plantation and that no other plantation would supply this facility with feedstock. Although in their second study they do evaluate corn as a potential alternative to wood, their model does not include any other plantations or ethanol production facilities. It is probable that a mature biorefinery industry would operate more like a network where multiple feedstock types are collected from dispersed locations and processed at multiple biorefineries within a region. Their modeling framework is not designed to accommodate this. Furthermore, it is also important to consider where and when the final products will be distributed once they are sold. None of the above studies address this aspect of biorefinery systems. The seasonality of feedstock supply availability will impact the operation, but so will the final product demand and distribution trends. Thus they should not be considered independently but rather as a continuous supply chain.

The research areas of life cycle analysis and net energy balance would directly benefit from a more robust biorefinery modeling framework. McLaughlin (2002, 2005) notes that the level of detail of conversion facility engineering data outweighs the data available for the other portions of a biorefinery supply chain, which limits the accuracy of life cycle analysis. This would also apply to net energy balance studies. Much of the current controversy of positive versus negative energy balance arises from inconsistent or different modeling approaches. But if a thorough modeling approach with defined system boundaries were presented as the common starting point upon
which to base such studies, the number of subjective differences between these studies might reduce significantly. This calls for a more holistic modeling approach that can quantify the entire supply chain operation rather than highlighting the production facility with modest treatment of the rest of the system.

Based on these observations, the literature reveals that there is no known model that integrates all of the planning aspects of the seven key questions into a single decision analysis framework. If there were such a modeling framework, the various research studies on biorefinery supply chain analysis might be brought together to support farm to consumer strategic thinking in a robust and integrated way. This need is what the present research is intended to fulfill.

1.4 Objectives and Definitions

The objectives of this dissertation are to establish a dynamic modeling framework for a biorefinery supply chain system and to illustrate the use of that framework by example. The framework will quantitatively describe the system and allow system optimization using mathematical programming. Specifically, the modeling framework will allow optimization of dynamic material flows and system configurations for feedstock supply sources and biorefineries. It is important to highlight some points regarding “models”, “systems”, and “optimization”. Mathematical models are approximate representations of actual systems, and the “optimal” solutions generated by such models are only optimal with respect to the model. Therefore, the effectiveness and value of “optimal” modeling solutions are only as good as the accuracy of the model and the values of the parameters taken on by the model. This means that although they may be
very reasonable approximations, optimal modeling solutions are not necessarily optimal for actual systems.

The intent of the stated objectives is to establish a useful modeling framework and not to offer modeling solutions for any real-world actual system. Thus the model solutions to be given here are only for purposes of validation and illustration. However, through validation and illustration, we shown that this model can actually provide a more complete and accurate portrayal for planning biorefinery supply chain operations than those presented in the literature. The modeling framework is designed to support the important planning decisions described in the seven key questions used in the literature review. Once again, these are:

1) which feedstocks to purchase,
2) when, from where, and how much to purchase of each feedstock,
3) where, how much, and how long to store each feedstock,
4) where, when, how many, and how big are biorefinery ,
5) how much of and when to produce each product,
6) how much of and where to distribute each product, and
7) how to plan for additional production capacity.

The mathematical modeling framework incorporates all of the seven questions. However, the validation and illustration examples will not include questions 4) and 7). If these planning aspects were included, the computational requirements for solving the mathematical programming problem would become impractical for purposes of this study.\(^1\)

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\(^1\) These modeling aspects would introduce integer programming constraints which would increase greatly the time required to find optimal solutions.
To clarify the objectives, it is important to define the terms used.

- **Dynamic** – This denotes system behavior over time. In this case, it implies that feedstock procurement and final product distribution will be considered over multiple time periods.

- **Modeling Framework** – This is a method or approach that is used to design and optimize a system. It includes the assumptions that define the scope of the system to be analyzed. It also includes the mathematical model that is used to design and optimize a system. Finally, the framework informs the model user as to what data should be collected as input parameters.

- **Biorefinery** – This is a manufacturing facility that converts various types of biomass materials (in this case lignocellulosic materials) into various types of products according to a dynamic procurement and production schedule. It includes onsite feedstock receiving, all processing and utilities, and final product storage.

- **Biorefinery Supply Chain** – This is a group of biorefineries in a defined region that receive feedstocks from sources inside the region and distribute products to demand locations inside the region. Note that the feedstock sources, intermediate feedstock storage, collection and transportation, and demand locations are all a part of the supply chain network.

- **Material Flows** – These refer to the quantity, origin, and destination of materials that flow from a source to a point of use. In this dissertation, the focus is on the flow of feedstock supplies, final products, and dollars and not on the chemical engineering flows.
within the biorefineries. These flows are dynamic, meaning occurring over a time horizon.

- **Configuration** – This refers to the arrangement of feedstock types, feedstock sources, and biorefinery locations that support the operation of a biorefinery network. Note that in a dynamic system, the configuration can change over time.

- **Mathematical Programming** – A discipline of techniques that minimize or maximize a function or set of functions under a set of equations or inequalities that constrain the value of the function or set of functions.

- **Optimization** – A minimization or maximization within the context of mathematical programming.

- **Optimal solution** – A complete set of output values for decision variables resulting from an optimization.

- **Decision variables** – The values to be determined as a result of an optimization. These values support decisions relating to the system being modeled.

This work demonstrates the applicability of mathematical programming models to lignocellulosic biorefinery network planning decisions. Note that the study is intended to establish a strategic planning decision model based on the anticipated structure of the developing biorefinery industry. As a part of establishing the modeling framework, this dissertation will discuss the types of parameter data that must be collected to support the use of the model. This part of the discussion will include suggested methods for data acquisition.

This dissertation is organized as a progression from model conceptualization to a discussion of model implementation and use.
Chapter 2: Mathematical Decision Model

Chapter 3: Discussion, Collection, and Definition of Parameter Data

Chapter 4: Sample Computer Implementation and Solution

Chapter 5: Discussion
2.0 MATHEMATICAL DECISION MODEL

This mathematical decision model seeks to establish an optimal plan for a network of integrated biorefineries as described in the objectives. (See section 1.4.) The mathematical model is an optimization model, consisting of system constraints and a profit function or "objective function". The optimization method consists of an algorithmic procedure which maximizes the objective function subject to constraint equations. In planning models, such as this, the profit is maximized, subject to the physical and economic constraints inherent to the system. The general approach to optimization is covered as a fundamental part of most operations research texts, beginning with linear programming and encompassing many other extensions and techniques.

This original mathematical decision model is set forth here one expression at a time. Each expression is preceded with introductory discussion that explains the aspect of the system that the expression is intended to represent. Immediately following each expression is an explanation of the mathematical behavior of the expression, as well as definitions and descriptions for specific variables, parameters, and technology coefficients as necessary. This presentation style will thus describe the system itself and the mathematical model for the system in tandem.

The model described here is intended to represent the physical biorefinery network in an accurate way while also preserving generality with respect to the details of the designs for the farming and harvest system, feedstock supply chain, conversion facility, and product distribution. While the model provides the structure for the system relationships, selection of specific
parameters would define the model for implementation. Each complete set of chosen parameters would represent an “instance” or “scenario” for the model. Data and parameters are covered in Chapter 3.

2.1 System Scope

The biorefinery system to be modeled consists of distinct elements and linkages from raw material supply through final product distribution. The assumed feedstock base is within an agricultural region consisting of individual farming operations. Each farming operation is assumed to be independent in terms of farming practices, land quality, crop quality, and economic decision making power. This implies unique land, crop, and economic characteristics for each farm. The farms produce feedstock materials of multiple types, which are made available to the biorefinery facilities at the discretion of the farm managers.\(^1\) These feedstock materials are harvested, collected, and transported to primary storage facilities where they await final delivery and conversion at their respective biorefineries.\(^2\) The harvesting, collection, transportation and storage activities incur a cost to the receiving biorefinery. Feedstock can decay when stored, which adversely affects feedstock quality and conversion yield at the biorefineries. Biorefineries can produce multiple end products using multiple feedstock types. All biorefineries within the system are assumed to be part of a single organization (or under the authority of a central decision

\(^1\) Each feedstock type considered in the present study is assumed to be one of multiple possible monocultures. However, Tilman et. al. (2006) suggest that low-input high-diversity grass cultures would provide substantial yield and environmental benefits. The model could accommodate these assumptions by applying corresponding parameter values.

\(^2\) Note that the generality of the system and modeling framework allow for different storage location assumptions. However, in this framework, each storage facility supplies only a single designated biorefinery. Further modeling research would be necessary to consider storage facilities capable of supplying multiple biorefineries.
maker), thus implying a common decision making process. The end products are stored in inventory at the biorefineries where they await distribution to customers. Stored inventories incur costs to the biorefineries. End products are distributed to demand locations and biorefineries receive revenue in return. Distribution to the customer incurs cost to the biorefineries. Demand shortages (including backorders) also incur cost to the biorefineries.

The entire system is dynamic, meaning that the operation occurs over a time horizon consisting of distinct periods. The decision policies will thus reflect a set of activities that occur over this time horizon. The activities include planting feedstock crops, feedstock harvesting and shipping, feedstock storage, feedstock conversion into products, storing products in inventory, and shipping end product to demand locations. The activities are described further in the model and parameter descriptions. Figure 1 provides a concise graphic that illustrates the structure of the system, as well as a high-level description of the mathematical model and model validation, which will be covered later.

2.2 Model Nomenclature

Model solutions, which guide biorefinery decisions, consist of determined values for decision variables. The decision variables are the extents to which certain activities are performed. The decision variables and their respective activities are described in Table-1. These variables provide information about the system that would guide agricultural land use and harvesting policies based on the feedstock harvest variable. The model links the supply of harvested materials to their storage and conversion into end products using the feedstock processing, feedstock storage, production, and distribution variables on the demand side. Finally, product inventory is
Shortage is cumulative demand minus cumulative distribution

Figure 1: System structure and model overview
Table 1: Decision Variables

<table>
<thead>
<tr>
<th>Variable*</th>
<th>Activity</th>
<th>Appears in Equations</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y_{iklm\tau}$</td>
<td>Feedstock Harvest</td>
<td>(1a), (1b), (2), (4), (5),</td>
<td>The amount of feedstock $l$ from farm $k$ harvested in period $m$ that is bound for conversion at the biorefinery at site $i$ in conversion period $\tau$.</td>
</tr>
<tr>
<td>$F_{s_{ilt}}$</td>
<td>Feedstock Storage</td>
<td>(5)</td>
<td>The amount of feedstock $l$ stored at site $i$ in time $t$.</td>
</tr>
<tr>
<td>$x_{iklnjp}$</td>
<td>Feedstock Processing</td>
<td>(3), (4), (5), (6), (8), (20), (21)</td>
<td>The amount of feedstock $l$ from farm $k$ harvested in period $m$ that is bound for conversion into product $p$ at the biorefinery at site $i$ in conversion period $j$.</td>
</tr>
<tr>
<td>$E_{ijp}$</td>
<td>Production</td>
<td>(7), (8), (11)</td>
<td>The total amount of product $p$ produced at the biorefinery at site $i$ in conversion period $j$.</td>
</tr>
<tr>
<td>$z_{injp}$</td>
<td>Distribution</td>
<td>(9), (11), (13), (18), (22)</td>
<td>The amount of product $p$ delivered from the biorefinery at site $i$ to the demand location $n$ during period $j$.</td>
</tr>
<tr>
<td>$I_{n_{ip}}$</td>
<td>Inventory</td>
<td>(10), (11), (14), (15), (23)</td>
<td>The amount of inventory of product $p$ at the biorefinery at site $i$ at the end of period $t$.</td>
</tr>
<tr>
<td>$s_{npj}$</td>
<td>Shortage</td>
<td>(12), (13), (14), (15), (24)</td>
<td>The amount of demand shortage (including backorders) of product $p$ at demand location $n$ in conversion period $j$.</td>
</tr>
<tr>
<td>$s_{Inf}^p$</td>
<td>Shortage-Inf</td>
<td>(14)</td>
<td>Aggregate inventory shortage for product $p$.</td>
</tr>
<tr>
<td>$s_{Inf}^{ip}$</td>
<td>Shortage-Inf</td>
<td>(15)</td>
<td>Inventory shortage of product $p$ at site $i$.</td>
</tr>
<tr>
<td>$s_{FsF}^F_l$</td>
<td>Shortage-FsF</td>
<td>(16)</td>
<td>Aggregate feedstock shortage for feedstock $l$.</td>
</tr>
<tr>
<td>$s_{FsF}^{il}$</td>
<td>Shortage-Fsf</td>
<td>(17)</td>
<td>Feedstock shortage for feedstock $l$ at site $i$.</td>
</tr>
</tbody>
</table>

*The variables $y$, $x$, $E$, and $z$ are “flow” processes. All others are “stock”.

56
modeled through the use of the inventory and shortage variables, which are a
direct result of demand and production. Together these variables comprise a set
of measurable outcomes that can be used to guide strategic decision making for
an integrated biorefinery network.

The parameters for the model constraints are constants which relate the
variables according to the physical structure of the system. These are given in
Table 2 and are also discussed in later sections. The parameters for the
objective function are all in terms of economic value, i.e. cost, revenue, or
economic penalty. Assigning economic values to the decision variables is what
allows the definition of an objective function.

2.3 Constraints

The following equations define the physical structure of the system.

\[
y_{iklm\tau} \geq 0 \ \forall \ i,k,l,m,\tau \in P_{klm}. \tag{1a}
\]

\[
y_{iklm\tau} = 0 \ \forall \ i,k,l,m,\tau \not\in P_{klm}. \tag{1b}
\]

These equations define a real variable \( y_{iklm\tau} \) as the quantity of feedstock type
\( l \in \text{FEEDSTOCKS} \) that is planted in period \( \tau \in \text{PLANTPERIODS} \) and shipped in
period \( m \in \text{HARVESTPERIODS} \) from farm \( k \in \text{FARMS} \) to the plant at site
\( i \in \text{SITES} \).

The set FEEDSTOCKS refers to all possible feedstocks (crop types or
materials) that can be harvested from farms. The set PLANTPERIODS is the
set of all periods in which feedstocks could be planted. The set
HARVESTPERIODS is the set of all periods in which feedstocks could be
harvested. Note that the harvest period \( m \) is assumed to be the period in
Table 2: Parameters for Constraints

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Appears in Equations</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_{kln}$</td>
<td>(1a), (1b), (5), (6)</td>
<td>Refers to a specific group of planting periods $\tau$ in which feedstock $l$ could have been harvested in period $m$ at farm $k$.</td>
</tr>
<tr>
<td>$a_{kl}$</td>
<td>(2)</td>
<td>The parameter $a_{kl}$ represents the inverse of the yield of feedstock $l$ at farm $k$.</td>
</tr>
<tr>
<td>$W_{kt}$</td>
<td>(2)</td>
<td>The maximum available land at farm $k$ in period $t$.</td>
</tr>
<tr>
<td>$c_{ilp}$</td>
<td>(6)</td>
<td>Denotes the capacity required to convert each unit of feedstock $l$ into product $p$ at plant $i$.</td>
</tr>
<tr>
<td>$f_{oi}$</td>
<td>(6)</td>
<td>Refers to site $i$’s feedstock conversion capacity per period.</td>
</tr>
<tr>
<td>$b_{iklnjp}$</td>
<td>(8)</td>
<td>Denotes the material conversion factor in units of product $p$ per unit of feedstock $l$, specific to each site $i$, farm $k$, period $m$, and conversion period $j$.</td>
</tr>
<tr>
<td>$In_{iop}$</td>
<td>(11)</td>
<td>Initial inventory of product $p$ at site $i$.</td>
</tr>
<tr>
<td>$D_{njp}$</td>
<td>(13)</td>
<td>Demand at location $n$ in period $j$ for product $p$.</td>
</tr>
<tr>
<td>$T$</td>
<td>(14), (15), (16), (17)</td>
<td>The final period in the planning horizon.</td>
</tr>
<tr>
<td>$InF_{p}$</td>
<td>(14)</td>
<td>The final aggregate inventory requirement for product $p$ for the whole system.</td>
</tr>
<tr>
<td>$Inf_{ip}$</td>
<td>(15)</td>
<td>The final inventory requirement for product $p$ at site $i$.</td>
</tr>
<tr>
<td>$FsF_{l}$</td>
<td>(16)</td>
<td>The final aggregate storage requirement for feedstock $l$.</td>
</tr>
<tr>
<td>$Fsfi_{i}$</td>
<td>(17)</td>
<td>The final storage requirement for feedstock $l$ at site $i$.</td>
</tr>
</tbody>
</table>

which feedstock is also shipped to storage to the biorefinery at site $i$. The set FARMS is the set of all farms in a given region. The set SITES is the set of all biorefinery locations.
Table 3: Parameters for Objective Function

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Appears in Equations</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R_{npj}$</td>
<td>(18)</td>
<td>Denotes the price per unit of p at location n in period j.</td>
</tr>
<tr>
<td>$c_{im}^{t}$</td>
<td>(19)</td>
<td>The discounted cost per period of initially opening a plant at site i.¹</td>
</tr>
<tr>
<td>$C_{iklmj}^{f}$</td>
<td>(20)</td>
<td>Costs of feedstock l for material, storage, and transportation from farm k to site i in period m converted in period j.</td>
</tr>
<tr>
<td>$C_{iklnjp}^{c}$</td>
<td>(21)</td>
<td>Costs of conversion of feedstock l into product p when shipped from farm k to site i in period m and converted in period j.</td>
</tr>
<tr>
<td>$d_{npj}$</td>
<td>(22)</td>
<td>Variable cost per unit of product p distributed from site i to location n in period j.</td>
</tr>
<tr>
<td>$h_{npj}$</td>
<td>(23)</td>
<td>Inventory holding cost for product p at site i in conversion period j.</td>
</tr>
<tr>
<td>$g_{npj}$</td>
<td>(24)</td>
<td>Shortage cost for product p at distribution location n in conversion period j.</td>
</tr>
<tr>
<td>sPEN</td>
<td>(25)</td>
<td>Penalty cost for not meeting final inventory or feedstock requirements at sites (shortage penalty).</td>
</tr>
</tbody>
</table>

The subset $P_{klm}$ refers to a specific group of planting periods $\tau$ in which feedstock l could have been harvested in period m at farm k. Thus the equations above indicate that $y_{iklm\tau}$ can be defined only when $\tau$ and m properly correspond. This prevents the model from allowing a feedstock to be planted in a nonsensical period, such as three years before it is harvested or being planted after being harvested, etc.

\[
\sum_{i} \sum_{m} \sum_{\tau} \sum_{l} a_{kl} \cdot y_{iklm\tau} \leq W_{kt} \quad \forall \, k,t .
\]  

¹ Note that fixed costs are not typically included in mathematical programs but are included here for purposes of comparison to other systems presented in the literature.
Equation (2) says that the sum of all feed stocks planted in all periods prior to
the current period and shipped in the current period through the end of the
planning horizon to all sites i must not exceed a certain maximum harvestable
amount of land. The parameter $a_{kl}$ represents the inverse of the yield of
feedstock l at farm k. The inverse yield converts $y_{iklmr}$ into an equivalent
amount of land, which may not exceed the maximum available land at farm k in
period t. This maximum land area is represented by the parameter $W_{kt}$.

$$x_{iklmjp} \geq 0 \quad \forall \ i,k,l,m,j,p . \quad (3)$$

Equation (3) defines a real variable $x_{iklmjp}$ to be the quantity of feedstock l
harvested and shipped from farm k to site i in period m and converted into
product $p \in \text{PRODUCTS}$ in conversion period j. PRODUCTS is the set of all
possible finished products that can be manufactured from the feedstocks.

$$\sum_{p} \sum_{j \geq m} x_{iklmjp} \leq \sum_{r \in P_{klm}} y_{iklmr} \quad \forall \ i,k,l,m . \quad (4)$$

In Equation (4), the amount of feedstock l harvested from farm k in period m
that is shipped to site i to be converted to all products p in all periods j greater
than or equal to m must not exceed what was harvested. The right hand side
term represents all quantities of feedstock l that were harvested in period m
from farm k and destined for site i. These quantities could have been planted
only during those periods $r \in P_{klm}$.
In Equation (5) the amount of feedstock $l$ stored for site $i$ as of the end of period $t$ is equal to the difference of what has been harvested as of the end of period $t$ minus what has been processed as of the end of period $t$.

The amount harvested is represented by the first term on the right hand side of the equation. This term is made up of those quantities of feedstock $l$ from all farms $k$ that are harvested in all periods $m$ up to and including the current period $t$. Each harvesting period $m$ is associated with the sum over its associated planting periods $\tau \in P_{klm}$.

The amount processed is represented by the second term on the right hand side of the equation. This is the sum of all quantities of feedstock $l$ from all farms $k$ that were harvested in all periods $m$ up to the current period $t$ and then converted. Conversion for these quantities could have occurred in any period from each harvesting period $m$ up through the current period $t$. These quantities could be converted into all products $p$.

$F_{slt} = \sum_{k} \sum_{m} \sum_{t} y_{iklm} - \sum_{k} \sum_{m} \sum_{j} \sum_{t} x_{iklmj} \forall i,l,t.$  

(5)

In Equation (6), the amount of total feedstock conversion in period $j$ at the biorefinery at site $i$ is limited by the feedstock conversion capacity at $i$. The parameter $f_{0i}$ refers to site $i$’s feedstock conversion capacity per period. The parameter $c_{ilp}$ denotes the capacity required to convert each unit of feedstock $l$ into product $p$ at plant $i$. The set PRODUCTS is the set of all possible products into which feedstock can be converted.

$\sum_{k} \sum_{l} \sum_{m} \sum_{j} c_{ilp} \times x_{iklmj} \leq f_{0i} \forall i,j.$  

(6)
Equation (7) defines the variable $E_{ijp}$ as the quantity of product $p$ produced at plant $i$ in conversion period $j$.

$$E_{ijp} \geq 0 \forall i,j,p.$$  \hfill (7)

In Equation (8) the expression on the left side of the equation measures the total quantity of product $p$ produced at plant $i$ in conversion period $j$ originating from all feedstocks $l$ and farms $k$. The parameter $b_{iklnjp}$ denotes the material conversion factor in units of product $p$ per unit of feedstock $l$, specific to each site $i$ and farm $k$. Note that the material conversion factor $b$ may also vary according to the quantity $(j-m)$, which is the number of periods over which the feedstock quantity is stored. Thus, feedstocks of different ages may have different conversion factors.

$$\sum_{k} \sum_{l} \sum_{m \leq j} b_{iklnjp} x_{iklnjp} = E_{ijp} \forall i,j,p.$$ \hfill (8)

Equation (9) defines a real variable to be the quantity of product $p$ shipped from plant $i$ to distribution location $n \in \text{DISTLOC}$ in period $j$. DISTLOC is the set of all possible distribution locations.

$$z_{injp} \geq 0 \forall i,n,j,p.$$ \hfill (9)

Equation (10) defines a real variable $I_{itp}$ to be the inventory level of product $p$ held at plant $i$ in conversion period $t$.

$$I_{itp} \geq 0 \forall i,t,p.$$ \hfill (10)
\[ I_{n_ip} = \sum_{j=1}^{i} E_{ipj} - \sum_{j=1}^{i} \sum_{n} z_{njp} + I_{n_ip} \quad \forall \, i,t,p \, . \quad (11) \]

In Equation (11), the inventory of product p at site i as of the end of period t is equal to what has been produced as of the end of period t minus what has been distributed as of the end of t, plus inventory on hand initially. The total amount of product p produced at i is represented by the first term on the right hand side of the equation. This is simply the production of product p over all conversion periods j up through the current period t. The total amount of product p distributed is represented by the second term on the right hand side of the equation. This is equal to the product distributed to all locations n over all conversion periods j up through the current period t.

\[ s_{np} \geq 0 \quad \forall \, n,t,p \, . \quad (12) \]

Equation (12) defines a real variable, \( s_{np} \), which measures the amount of shortage of product p at distribution location n at the end of period t.

\[ \sum_{j=1}^{i} D_{njp} - \sum_{j=1}^{i} \sum_{i} z_{njp} = s_{np} \quad \forall \, n,t,p \, . \quad (13) \]

In Equation (13), the demand for product p at location n up through the current period t minus the distribution of product p from all biorefinery sites i up through the current period t is equal to the total product shortage of product p at location n at the end of period t.

\[ \sum_{i} I_{n_ip} + s_{np}^{inf} \geq I_{n_Fp} \quad \forall \, p \, . \quad (14) \]
In Equation (14), the sum of all inventories of product \( p \) over all sites \( i \) at the end of period \( T \) plus the shortage of product \( p \) at all distribution locations \( n \) at the end of period \( T \) must be greater than or equal to the final aggregate inventory requirement for product \( p \). The parameter \( T \) is the final period in the planning horizon. The parameter \( \text{Inf}_p \) is the final aggregate inventory requirement for product \( p \) for the whole system.

\[
\text{Inf}_{\text{Ip}} + \text{Inf}^\text{s}_{\text{Ip}} \geq \text{Inf}_p \quad \forall \text{i,p}.
\]  

(15)

In Equation (15), the final inventory of product \( p \) at site \( i \) must be greater than or equal to the final inventory requirement for product \( p \) at site \( i \). The parameter \( \text{Inf}_p \) is the final inventory requirement for product \( p \) at site \( i \).

\[
\sum_i \text{Fs}_{\text{If}} + \text{Fs}^\text{sF}_{\text{I}} \geq \text{FsF}_l \quad \forall \text{l}.
\]  

(16)

In Equation (16), the sum of the final storage quantities for feedstock \( l \) over all sites \( i \) must be at least as great as the final aggregate storage requirement for feedstock \( l \). The parameter \( \text{FsF}_l \) is the final aggregate storage requirement for feedstock \( l \).

\[
\text{Fs}_{\text{If}} + \text{Fs}^\text{sF}_{\text{I}} \geq \text{FsF}_{\text{Il}} \quad \forall \text{i,l}.
\]  

(17)

In Equation (17), the final storage quantity for feedstock \( l \) at site \( i \) must be at least as great as the final storage requirement for feedstock \( l \) at site \( i \). The parameter \( \text{FsF}_{\text{Il}} \) is the final storage requirement for feedstock \( l \) at site \( i \).
2.4 Objective Function

The objective function for the model is the revenue from all product distribution minus all costs. Equation 18 represents the revenue, while all other equations in this section are costs.

\[ \sum_{j} \sum_{n} \sum_{p} R_{njp} \sum_{i} z_{njp} \cdot \]  \hspace{1cm} (18)

In Equation (18), total revenue is defined by the sum of the values of all products p shipped from all plants i to all distribution locations n over all conversion periods j. The parameter \( R_{njp} \) denotes the price per unit of p at location n in conversion period j.

\[ \sum_{i} \sum_{m} c_{im}^{f} \cdot \]  \hspace{1cm} (19)

In Equation (19), total fixed plants costs are the per period discounted costs of construction and startup for all facilities i.\(^1\) The discounted cost per period of initially opening a plant at site i is given by the parameter, \( c_{im}^{f} \).

\[ \sum_{i} \sum_{k} \sum_{l} \sum_{m} \sum_{j} C_{iklnj}^{f} \sum_{p} x_{iklnjp} \cdot \]  \hspace{1cm} (20)

In Equation (20), the total variable costs of feedstock for material, storage, and transportation are the sum of the costs for all feedstocks l shipped from all farms k to all sites i in all periods m and converted in all conversion periods j. The variable cost \( C_{iklnj}^{f} \) is unique to each i,k,l,m,j.

\(^1\) Fixed costs are generally not included in mathematical programs but are included here for purposes of comparison to other systems in the literature.
\[ \sum_{i} \sum_{k} \sum_{l} \sum_{m} \sum_{j} \sum_{p} C_{iklmjp}^c \times x_{iklmjp}, \]  

(21)

In Equation (21), the total variable costs of conversion are the sum of the costs for all feedstocks \( l \) converted into all products \( p \) that were shipped from all farms \( k \) to all sites \( i \) in all harvest periods \( m \) and converted in all periods \( j \). The variable cost \( C_{iklmjp}^c \) is unique to each \( i,k,l,m,j,p \).

\[ \sum_{i} \sum_{n} \sum_{j} \sum_{p} d_{nip} x_{nip}. \]  

(22)

In Equation (22), the total variable cost of distribution is the sum of all costs for distribution of all products \( p \) from all sites \( i \) to all locations \( n \) in all periods \( j \). The parameter \( d_{nip} \) is the variable distribution cost parameter unique to each \( i,n,j,p \).

\[ \sum_{i} \sum_{j} \sum_{p} h_{ijp} x_{ijp}. \]  

(23)

In Equation (23), total inventory holding costs are the sum of holding costs for all products \( p \) at all plants \( i \) over all conversion periods \( j \). The parameter \( h_{ijp} \) denotes the holding cost unique to each \( i,j,p \).

\[ \sum_{n} \sum_{j} \sum_{p} g_{npj} x_{npj}. \]  

(24)

In Equation (24), the total product shortage costs are the sum of shortage costs for all products \( p \) at all distribution locations \( n \) over all conversion periods \( j \). The parameter \( g_{npj} \) denotes the shortage cost unique to each \( n,j,p \).
Equation (25) expresses the amount of “penalty” cost incurred when final conditions are not met per the shortage variables in equations (14), (15), (16), and (17). sPEN is the “penalty” constant for each unit of shortage in any of the shortage variables. A very large sPEN ensures that final conditions are met.

2.5 Useful Model Extensions

There are two noteworthy extensions to the model that has been described thus far. These extensions are included because they would be important aspects of a real implementation, but they are not used in the sample implementation and solution here because the constraints would greatly increase the computational complexity\(^1\), making run times for experimentation impractical. These two extensions tie directly back to modeling the questions 4) and 7) as discussed in the literature review and objectives.

2.5.1 Facility Siting (Question #4)

Consider a binary variable, \( v_{im} \), which indicates whether a facility exists at site \( i \) in period \( m \), where

\[
v_{im} = \begin{cases} 
1, & \text{if a conversion facility exists as of period } m \text{ at site } i \\
0, & \text{otherwise}
\end{cases}
\]

(26)

Equation (26) would allow the model to determine when and where facilities are constructed. It can be assumed that if a facility first exists (is constructed)

\(^1\) This is due to integer programming constraints.
at the beginning of a particular time horizon in period \( m=1 \), that it will also exist for the rest of that time horizon. Under this assumption for modeling this parameter, we have the constraint

\[
v_{im} \leq v_{i(m+1)} \quad \forall \ i,m \in 1..(M-1). \tag{27}
\]

Equation (27) means that once constructed, a facility must continue to exist over the planning horizon. In the sample implementation to follow, it will be assumed that \( v_{im} = 1 \) for each site \( i \), meaning that a facility exists at that site as of period \( m=1 \) and by equation (27), in all periods thereafter. However, in a real system, it is unlikely that all facilities would be constructed and begin operation at the same time. In fact, the expectation would likely be that as the biorefinery industry grows due to product demand, more plants will be constructed over time.

In siting biorefineries, there will necessarily be constraints that describe the requirements or limitations of the geographical dispersion for the facilities. This would require the additional following variables and constraints.

\[
q_i = \begin{cases} 
1, & \text{if a conversion facility ever exists at site } i \\
0, & \text{otherwise}
\end{cases} \tag{28}
\]

Equation (28) defines a binary variable \( q_i \) for indicating if a facility is “sited” at site \( i \). This must correspond with the “existence” of the facility in each period. This is expressed by

\[
\sum_m v_{im} \leq q_i \quad \forall \ i,m. \tag{29}
\]
Equation (29) states that a facility may only exist at site i in one or more periods if it is sited there. Although this distinction seems abstract, note that \( q_i \) is independent of time. It says that either a facility will eventually exist at site i or it will not. This becomes important in planning the siting of multiple biorefineries within a specified geographical subregion.

Consider multiple geographic subregions \( r = 1, r = 2, r = 3 \ldots \) any of which may overlap one or more of the others. These make up the set SUBREGIONS. In order to restrict the number of biorefineries within any one of the subregions \( r \), the following constraint applies.

\[
\sum_{i \in Q_r} q_i \leq Q_{r, \text{max}} \quad \forall \ r \in \text{SUBREGIONS}.
\] (30)

Equation (30) means that the number of facilities sited within a given subregion \( r \) may not exceed a certain number, defined by the parameter, \( Q_{r, \text{max}} \). Those sites i within a subregion r comprise, \( Q_r \), which is a subset of the set SITES. Thus for each \( r \), \( Q_r \) is the set of candidate sites for biorefinery construction, and \( Q_{r, \text{max}} \) is the limit on how many candidates may be chosen from \( Q_r \). This formulation permits a very flexible interpretation of how planning for facility siting may be incorporated into the overall optimization model.

2.5.2 Capacity Expansion (Question #7)

Recall equation (6) which constrains the amount of feedstock converted at a facility by that facility’s capacity. Now suppose that at some point after initial facility construction that it becomes economically favorable to increase that capacity. To incorporate these possibilities into the model, the following variables and constraints would be introduced.
Equation (31) defines the amount of per period conversion capacity added by period $j$ at the facility at site $i$, within the capacity range lambda. Capacity increases must be modeled in specific ranges since new processing equipment is typically not available in every conceivable size.

$$u_{ij\lambda} \geq 0 \forall i,j,\lambda.$$  \hfill (31)

Equations (32) and (33) define a binary variable that designates which added capacity range $\lambda$ is installed at facility $i$ in period $j$, and that only one capacity range is permitted at any facility $i$ per period $j$.

$$e_{ij\lambda} = \begin{cases} 1, & \text{if capacity added by period } j \text{ at site } i \text{ is within range } \lambda \\ 0, & \text{otherwise} \end{cases}. \hfill (32)$$

$$\sum_k e_{ij\lambda} = 1 \forall i,j. \hfill (33)$$

To incorporate capacity additions into the upper limit of processing, equation (6) becomes

$$\sum_k \sum_m \sum_{p} c_{ip} * x_{iklmnp} \leq f_{0i} * v_{ij} + \sum_{\lambda} u_{ij\lambda} * v_{ij} \forall i,j. \hfill (34)$$

This constrains the processing capacity by the initial capacity at the period of initial construction, as well as any capacity additions that take place in later periods up to the current conversion period $j$. The variable $u_{ij\lambda}$ is multiplied by $v_{ij}$ to prevent capacity additions to a facility before it exists.

The upper and lower bounds of an added capacity range are given by

$$U^{-}_{ij\lambda} * e_{ij\lambda} \leq u_{ij\lambda} \leq U^{+}_{ij\lambda} * e_{ij\lambda} \forall i,j,\lambda. \hfill (35)$$
In Equation (33), \( U_{ij\lambda} \) and \( U^+_{ij\lambda} \) are the lower and upper bounds, respectively, for the added capacity range in period \( j \) at site \( i \) for range \( \lambda \). Note that the range bounds only apply if the facility at site \( i \) is actually in range \( \lambda \), since \( e_{ij\lambda} \) would otherwise be zero.

If we wanted to strictly disallow capacity decreases from occurring, we would need to introduce

\[
u_{ij\lambda} \leq u_{i(j+1)\lambda} \quad \forall \ i, j=1..(J-1), \lambda . \tag{36}\]

Equation (34) simply states that the total added capacity by period \( j+1 \) cannot be smaller than the total added capacity by period \( j \).

Finally, the objective function would also need to include the additional cost term

\[
\sum_{\lambda} \sum_{i} \sum_{j} c_{ij\lambda} v_{ij\lambda} u_{ij\lambda} . \tag{37}
\]

Equation (34) denotes the total cost of facility expansions at all sites \( i \) over all periods \( j \) over all added capacity ranges \( \lambda \). The parameter \( c_{ij\lambda} \) is the cost of facility expansion at site \( i \) in period \( j \).
3.0 DISCUSSION, COLLECTION, AND DEFINITION OF PARAMETER DATA

Parameter data must be carefully considered within the context of the actual system the model is intended to describe. Model formulation must be a useful depiction of the actual system structure, but without accurate estimation of parameter values, model solutions are not valid. Actual model implementation by a company or government entity would require scenario-specific research on parameter values. For example, an enterprise using this model to help launch a biorefinery program would likely mobilize a team of subject matter experts to derive parameter values along with an operations research team to test multiple scenarios for actual optimization and sensitivity analysis.

This section serves three purposes:
1) Discusses each model parameter with respect to actual system context.
2) Offers explanation of how parameter data would be collected or determined for actual implementation.
3) Defines values of each parameter for illustration by example.

3.1 Biorefinery Data

A biorefinery facility includes feedstock storage, processes for feedstock conversion to an end product, and end product inventories. Technologies of lignocellulosic biomass conversion to ethanol are mechanical, chemical, and biochemical in nature and form a complex subsystem within the overall supply chain. The biochemical processes in particular are prone to a variety of nonlinear yield responses to reaction conditions, such as temperature and
reagent concentration, making these processes very sensitive and important to optimize daily in real time. However, since the focus of this study is for a longer term planning horizon, these conversion process issues will not be considered in detail here.

Authors in the literature review above have developed operating and cost parameters for biorefineries. In depth engineering design studies are becoming more detailed and technologically progressive. However, these analyses have been developed with limited focus on how the feedstock procurement and product distribution strategies will impact the designs that are already well underway. So far, the focus is on facility design and engineering, with some attention being paid also to feedstock harvesting and collection equipment. However, the coordination and scheduling of the feedstock supply chain and distribution require additional research. In particular, the supply chain must be designed in tandem with the chemical conversion facility instead of them being developed independently with the assumption that they will somehow conveniently link together once developed.

The model considers the following aspects related to the biorefinery facility: material handling requirements, total biorefinery capacity, material conversion factors or “technology coefficients”, construction costs, capital costs of expansion, delivered feedstock costs, and facility operating costs. Finally, the dissertation will include a discussion of original biorefinery parameter design for all of the following parameters.

3.1.1 Material Handling Requirements

The material handling requirement parameter represents the amount of biorefinery capacity consumed per unit of feedstock, given by the parameter,
This parameter is used in equation (6). The value is unique to each feedstock type \( l \), biorefinery site \( i \), and product \( p \). If we assume that feedstock is measured in volumetric units, such as bushels or cubic meters, and biorefinery capacity is measured in units of mass, such as metric tons, this parameter can represent a bulk density. This density can then be used to convert feedstock amount into units of mass. If desired, this parameter can also incorporate conversion from moisture levels in raw feedstock to dried feedstock. Finally, mechanical processing at storage sites or the biorefinery can increase density from “bulk” to “final”, where final is the density of feedstock entering the biochemical conversion process.

For actual model implementations, subject matter experts would need to establish \( c_{ilp} \) by understanding the relationships between bulk density of stored material and final density of material just before conversion. Biorefinery developers would commission agricultural engineers to conduct case specific pilot tests. Key research variables include the conditions during storage, the method of mechanical cleaning and sizing, and the application of feedstock dryers, if applicable. It should be noted that drying and mechanical preprocessing have an effect on the final yield of the biochemical conversion. This is because changes in the composition and physical structure of the feedstock impact the mass transport during chemical reactions. This aspect of material handling will not be included in the model.

The value of \( c_{ilp} \) used in the illustration example will be 0.85 to represent a 15% moisture content (wet basis) in the received feedstock. This value falls within the range of assumptions used by Perlack & Turhollow (2003), Kerstetter (2001), and Aden et. al. (2002). This effectively converts the mass of
feedstock into dry mass, which is commonly used to measure feedstock processing capacity.

3.1.2 Total Initial Capacity

The initial designed capacity for a biorefinery is given by

\[ f_0, \]

This parameter is also used in equation (6) and is unique to each biorefinery site \( i \). This will be measured in units of mass, such as metric tons.

For actual model implementations, biorefinery developers would determine the value of \( f_0 \) by first assessing the business case for building a biorefinery. This is normally done with a feasibility study, which includes a strategic assessment of feedstock availability, market demand for products, survey of available technologies, and broader considerations of facility siting. Another way to determine \( f_0 \) would be to use the present model as a way of testing the sensitivity of total profit to biorefinery size. There are a growing number of consultants who specialize in feasibility and design studies, such as Fagen, Inc. and BBI International. These values are somewhat larger than the average present day corn based facilities as well as the prototype facility in Aden et. al. (2002). Rather these capacities and more similar to the scale used in Lynd & Wyman et. al. (2002). The values of \( f_0 \) used in the illustration example are given in Table 4.

3.1.3 Material Conversion Factors

The parameter that dictates the yield of product per unit feedstock is given by

\[ b_{iklmp}, \]
Table 4: Feedstock Processing Capacities

<table>
<thead>
<tr>
<th>Facility (i)</th>
<th>Feedstock Processing Capacity (million dry lbs / month)</th>
<th>Feedstock Processing Capacity (1000 dry metric tons / month)</th>
<th>Feedstock Processing Capacity (1000 wet metric tons / month)</th>
<th>Production Capacity, Ethanol Equivalents* (million gallons per year)</th>
</tr>
</thead>
<tbody>
<tr>
<td>i=1</td>
<td>113</td>
<td>51.5</td>
<td>60.7</td>
<td>120</td>
</tr>
<tr>
<td>i=2</td>
<td>142</td>
<td>64.4</td>
<td>75.9</td>
<td>150</td>
</tr>
<tr>
<td>i=3</td>
<td>189</td>
<td>86.0</td>
<td>101.1</td>
<td>200</td>
</tr>
</tbody>
</table>

*Assumes conversion of 100% corn stover.

which is used in equation (8). This is also known as a technology coefficient. Material conversion factors are unique to each combination of biorefinery site i, farm k, feedstock l, period m, conversion period j, and product p. They are measured in units of mass or volume of product per unit of mass or volume of feedstock. Conversion factors may vary by biorefinery since each may have its own equipment configuration or conversion efficiency according to scale, process conditions, and control settings. Conversion factors will vary by farm of origin since the material quality is a function of farming practices, land quality, and other agricultural factors. Each feedstock type will have a unique composition as well. The difference between month harvested and month converted to product impacts seasonal material quality differences, loss due to natural decay, and other time dependent feedstock characteristics. Finally, this conversion factor also depends on the type of product to be manufactured since a given amount of feedstock will yield different amounts of products based on their respective underlying chemical reactions.
For actual model implementations conversion coefficients would be determined by chemical process engineers in pilot testing before construction. However, it is important to note that this parameter is a matter of intense research focus. Government, academic, and industry researchers are all focusing on this technology coefficient as the key to unlocking the potential of the entire biorefinery industry. Thus the values are constantly changing and improving as innovations are made. Furthermore, it is a value which will change not only due to the factors just described, but also due to changes made by process engineers who optimize their facility over time with minor process adjustments.

The values of $b_{ijklmp}$ used in the illustration are a function of the material conversion factor (technology coefficient) and the feedstock decay profile. Table 5 gives the technology coefficients for converting corn and wheat into ethanol and succinic acid.1

Table 5: Chemical Conversion Technology Coefficients

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Product</th>
<th>lbs product per pound dry feedstock</th>
<th>gallons product per pound dry feedstock</th>
<th>liters product / kg dry feedstock</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn stover</td>
<td>Ethanol</td>
<td>0.29</td>
<td>0.045</td>
<td>0.374</td>
</tr>
<tr>
<td>Corn stover</td>
<td>Succinic Acid</td>
<td>0.29</td>
<td>0.022</td>
<td>0.187</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>Ethanol</td>
<td>0.25</td>
<td>0.038</td>
<td>0.319</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>Succinic Acid</td>
<td>0.25</td>
<td>0.019</td>
<td>0.159</td>
</tr>
</tbody>
</table>

1 Succinic acid is chosen as an example co-product since it is used by Lynd & Wyman et. al. (2002), who make data available. This compound is a high value chemical intermediate used in the production of surfactants, consumer products, and pharmaceuticals.
Table 6: Feedstock Decay Profile

<table>
<thead>
<tr>
<th>Months of Storage at 15% moisture (wet basis)</th>
<th>Fraction of Remaining Dry Corn Stover</th>
<th>Fraction of Remaining Dry Wheat Straw</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.986</td>
<td>0.998</td>
</tr>
<tr>
<td>2</td>
<td>0.971</td>
<td>0.995</td>
</tr>
<tr>
<td>3</td>
<td>0.957</td>
<td>0.993</td>
</tr>
<tr>
<td>4</td>
<td>0.943</td>
<td>0.990</td>
</tr>
<tr>
<td>5</td>
<td>0.929</td>
<td>0.988</td>
</tr>
<tr>
<td>6 and all months thereafter</td>
<td>0.914</td>
<td>0.985</td>
</tr>
</tbody>
</table>

These values represent a decay of 1.4% of the original dry mass of corn stover (Sokhansanj, 2006) and a decay of 0.25% of the original dry mass of wheat straw (Summers, 2003). The number of months of storage is taken as the difference between period converted and period shipped, or by model indices as $j - m$.

3.1.4 Construction and Startup Cost

The discounted cost of construction and startup for the biorefinery is given by

$$c_{im}^f.$$ 

This parameter is used in equation (19) and is unique to each potential biorefinery site $i$ and harvest period $m$. As with any production facility, the capital cost of the biorefinery is recovered over a period of years. A discounted cash flow model is used to relate cost to revenue on a periodic basis.

For actual model implementations the values of $c_{im}^f$ would be determined in contract negotiations with design and construction firms and
financiers. Construction firms set the contract price and financiers set the conditions of the financing arrangements. There are a number of firms who specialize in design and construction of corn ethanol facilities, and these are the likely candidates for biorefinery construction. These include Fagen, Inc. (2006) and Broin Companies (2006).

The values for construction and startup cost used in the illustration example are derived by using the total installed capital costs for the prototype plant in Aden et. al. Facility capacity is scaled from the prototype plant using a 0.8 scaling factor according to the following equation:

$$C_2 = C_1^* \left(\frac{M_2}{M_1}\right)^{0.8}$$  \hspace{1cm} (38)

where $C_1$ and $C_2$ are the total installed capital costs for a base case and scaled facility, respectively, and where $M_1$ and $M_2$ are the production capacities for a base case and scaled facility. The 0.8 scaling factor is in line with Jenkins (1997) and Peters & Timmerhaus (1980). The nominal cash flows are given in Table 7.

The discounted cost of capital expansion is given by,

$$c_{ij\lambda}^v$$

This parameter is used in equation (37) and is unique to each potential biorefinery site $i$ and harvest period $m$. As described in section 2.5.2, capacity expansion is an important aspect of modeling the biorefinery supply chain network.
Table 7: Biorefinery Capacity and Construction and Startup Costs

<table>
<thead>
<tr>
<th>Facility (i)</th>
<th>Production Capacity (millions of gallons / year)</th>
<th>Production Capacity (millions of liters / year)</th>
<th>Present Value of Total Installed Facility &amp; Services* (millions of dollars)</th>
<th>Nominal Cost per Month at 7% loan rate and 30 year life</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base Case**</td>
<td>69.3</td>
<td>262.5</td>
<td>200.3</td>
<td>2.3</td>
</tr>
<tr>
<td>(prototype, Aden et. al.)</td>
<td>i=1</td>
<td>120</td>
<td>454.5</td>
<td>310.7</td>
</tr>
<tr>
<td></td>
<td>i=2</td>
<td>150</td>
<td>568.2</td>
<td>371.5</td>
</tr>
<tr>
<td></td>
<td>i=3</td>
<td>200</td>
<td>757.5</td>
<td>467.6</td>
</tr>
</tbody>
</table>

*Uses 0.8 scaling factor.
**Base case in 2002 dollars.

For actual model implementations the values of \( c_{ij}^{y} \) would be determined much like the values of \( c_{im}^{c} \). The same parties would be involved and costs would be treated in the same way. It should be noted, however, that it would be more difficult to predict the values of \( c_{ij}^{y} \) for some future period. Inflation, supply and demand for construction services, and changes in interest rates could all impact the actual values of \( c_{ij}^{y} \). Therefore, for modeling purposes, subject matter experts must rely on forecasts for expansion.

The added capacity bound parameters are given by

\[
U_{ij}^{-} \text{ and } U_{ij}^{+} .
\]

These simply place limits on the added capacity ranges in which a facility may lie for a given period. They are used in equation (35). It is measured in units of mass or volume.

For actual model implementations the values of \( U_{ij}^{-} \) and \( U_{ij}^{+} \) would be estimated based on anticipated available technologies, projected growth in
market demand, and assumed availability of project funding. The engineering
design firms mentioned above would assist developers in determining these
costs.

Because capital expansion will not be modeled in the illustration
eexample, values for \( U_{ij\lambda}^- \) and \( U_{ij\lambda}^+ \) are not derived here.

### 3.1.5 Total Feedstock Costs

The total cost per unit of feedstock is given by

\[
C_{iklmj}^f
\]

This parameter is used in equation (20). Each value is unique to the
combination of biorefinery site \( i \), farm \( k \), feedstock \( l \), harvest month \( m \), and
conversion month \( j \). There are several system aspects that affect this parameter.
Each farm can charge unique harvested material prices for each feedstock type.
This price would be based on the farmer’s cost of production. In many cases
the biomass feedstock is actually a residual material, as in the case of corn
stover or wheat straw. Since the farmer receives revenue for the grain portions,
the value of the residual will be set by the farmer in terms of both cost of
production and loss of nutrition to the soil. This is because the residual material
normally stays in the field to be tilled under and decomposed. This lost value to
the farmer can be measured in terms of replacement nutrients by fertilizers.
The nutritional needs and costs of fertilizers vary annually based on region and
year, making this a complex aspect of the parameter.

\( C_{iklmj}^f \) also includes the cost of transportation from the farm to the
storage facility. Each transportation cost is a function of the farm location and
site location. Because fuel prices fluctuate, this cost can also vary with time,
which impacts shipping decisions. Storage cost, a function of storage duration,
is also included in $C^f_{iklmj}$. This is represented by the difference between the month converted ($j$) and month received ($m$) which is equal to the storage duration.

For actual model implementations the values of this parameter would be highly dependent on case-specific factors, as just described. Thus subject matter experts, such as agricultural economists, would estimate the values of this parameter based on regional economic conditions and communications with farmers and shipping companies. The values of feedstock cost used in the illustration example are made up of field collection, transportation, storage, and farmer payments. These values are based on values taken from Perlack & Turhollow (2003) and Kerstetter et. al. (2001) for corn stover and wheat straw, respectively. These are given below in Table 8. The metric equivalent of Table 8 is given in Table 9.

### Table 8: Components of Feedstock Cost

<table>
<thead>
<tr>
<th>Component of Parameter</th>
<th>Units (15% moisture wet basis)</th>
<th>Corn Stover</th>
<th>Wheat Straw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collection</td>
<td>$ / ton</td>
<td>15</td>
<td>12.15</td>
</tr>
<tr>
<td>Transport</td>
<td>$ / ton-mile</td>
<td>0.28</td>
<td>0.2</td>
</tr>
<tr>
<td>Storage</td>
<td>$ / ton-month</td>
<td>0.83</td>
<td>1.17</td>
</tr>
<tr>
<td>Farmer Payment</td>
<td>$ / ton</td>
<td>10</td>
<td>4</td>
</tr>
</tbody>
</table>

### 3.1.6 Operating Costs

The costs of material conversion and general plant operation are given by

$C^e_{iklmjp}$. 
Table 9: Components of Feedstock Cost – Metric Units

<table>
<thead>
<tr>
<th>Component of Parameter</th>
<th>Units (15% moisture wet basis)</th>
<th>Corn Stover</th>
<th>Wheat Straw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Collection</td>
<td>$ / metric ton</td>
<td>16.53</td>
<td>13.39</td>
</tr>
<tr>
<td>Transport</td>
<td>$ / metric ton – km</td>
<td>0.19</td>
<td>0.14</td>
</tr>
<tr>
<td>Storage</td>
<td>$ / metric ton – month</td>
<td>0.92</td>
<td>1.29</td>
</tr>
<tr>
<td>Farmer Payment</td>
<td>$ / metric ton</td>
<td>11.02</td>
<td>4.41</td>
</tr>
</tbody>
</table>

This parameter is used in equation (21). Each value is unique to the combination of biorefinery site i, farm k, feedstock l, harvest month m, conversion month j, and product type p. The parameter represents all non-feedstock operating costs, including operation and maintenance of the conversion process, labor, utilities, engineering, general and administrative costs.

For actual model implementations these values would be determined by biorefinery developers and subject matter experts. They would use chemical engineering cost estimation methods or engineering consulting firms to estimate these costs. Such methods typically rely on standardized guides, references, and cost indices that pertain to specific pieces of process equipment. The costs are generally a function of the technology and size of the process equipment. Engineering firms would further refine the estimates with data from equipment manufacturers as well as utility and labor rates and other costs. The values used in the implementation example are given in Table 10.
Table 10: Conversion & Operating Costs

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Product</th>
<th>Conversion Cost ($ / dry ton feedstock)</th>
<th>Conversion Cost ($ / dry metric ton feedstock)</th>
<th>Conversion Cost ($ / gallon product)**</th>
<th>Conversion Cost ($ / liter product)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn stover</td>
<td>Ethanol</td>
<td>20.54</td>
<td>22.64</td>
<td>0.229</td>
<td>0.060</td>
</tr>
<tr>
<td>Corn stover</td>
<td>Succinic Acid</td>
<td>26.74</td>
<td>29.47</td>
<td>0.596</td>
<td>0.157</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>Ethanol</td>
<td>24.08</td>
<td>26.53</td>
<td>0.268</td>
<td>0.070</td>
</tr>
<tr>
<td>Wheat straw*</td>
<td>Succinic Acid</td>
<td>31.34</td>
<td>34.54</td>
<td>0.699</td>
<td>0.184</td>
</tr>
</tbody>
</table>

*Assumes that lower yield from wheat straw increases conversion costs proportionally.  
**Does not include feedstock costs.

These values are taken from Lynd & Wyman et. al. (2005). Conversion costs include non-feedstock raw materials, waste disposal, electricity, labor, maintenance, operating overhead, taxes, and insurance. Succinic acid conversion costs also include the cost of microfiltering supplies.

3.2 Agricultural Data

The base of feedstock supply is assumed to be a set of farms. Although biomass can potentially come from many types of sources, the scope will be limited to farms to simplify the analysis. The model allows each farm to have exactly the same feedstock options (although solutions may not exhibit use of all options). In the context of a biorefinery industry, farmers will not necessarily be limited to biorefineries as buyers of biomass. In fact, farmers will likely have other options for feedstock materials, such as animal feed or bedding, sale to other industrial customers, or tilling biomass back into soil for
nutritional purposes. Thus farmers may choose not to participate in such an industry at all depending on economic alternatives. Farmers and biorefinery managers could arrange contract pricing or the price could be adjusted from period to period.

The proposed feedstocks for the illustration example are corn stover and wheat straw. These selections are based on the fact that many of the studies and parties developing these projects are considering these resources. (See section 1.3 Literature Review.) Although other candidates, such as switchgrass or other grasses could have been included to model even more feedstocks, the computational complexity of the illustration example would have been impractical.\(^1\)

The model is designed to determine the annual land requirements assuming certain feedstock availability levels at farms. These availabilities take into account agricultural yield, soil requirements for crop residues being tilled back into the soil, and extent of farmer participation. The availability level is defined as a parameter in the model and is discussed below. Ultimately, the feedstock and land requirements must correspond geographically with the siting of the biorefineries themselves. This is addressed in section 3.4 Spatial Modeling Considerations.

### 3.2.1 Treatment of Seasons

Agricultural feedstocks are “produced”, meaning ready for harvest, only at certain times throughout a year. These periods are indexed by the “tau” subscript throughout the model. Using tau facilitates the correct correspondence between planting and harvest periods. Each feedstock has a

---

\(^1\) This is due to integer programming constraints.
designated growing season and a typical harvest season. These seasons may vary slightly depending on region, climate, annual weather, and farming practices. The model allows these seasons to be designated by certain periods. These are given in Table 11.

### Table 11: Planting and Harvest Seasons

<table>
<thead>
<tr>
<th>Feedstock</th>
<th>Allowable Planting Months</th>
<th>Allowable Harvesting Months</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn stover</td>
<td>March and April</td>
<td>October and November</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>September and October</td>
<td>July and August</td>
</tr>
</tbody>
</table>

#### 3.2.2 Feedstock Availability

The inverse of availability of feedstock per unit land area is given by

\[ a_{ki} \]

The inverse of agricultural yield is used, i.e. “land area per unit feedstock harvested”, for modeling convenience. This parameter is used in equation (2) and is unique to each farm \( k \) and feedstock \( l \). The value represents a composite of factors including agricultural yield, amount of material available after nutritional soil requirements, and the willingness of farmers to sell the biomass feedstocks. Agricultural yield itself is dependent upon many factors including regional soil conditions and climate, farming practices, pest damage, and annual weather variations.
Many farmers rely on post-harvest residual crop biomass as a soil nutrition agent. To some extent, this loss can be replaced by fertilizers and by limiting erosion, but this comes with an operational cost to the farmer. Thus, there is a balance between the cost of sustaining fertile soil and the potential revenue from the sale of residual crop biomass. Aside from soil considerations, farmers may have competing economic alternatives for their residual biomass, such as animal bedding or sale to other industries in need of fibers. Thus their participation may be limited based on the attractiveness of the competing offers.

For actual model implementations this parameter would be determined based on historical agricultural yield statistics, survey of local farming practices (with a particular focus on amount of residual retained for soil nutrition), and market analysis of competing economic alternatives. This would likely be done as part of a feasibility analysis, as described in the biorefinery parameters section. Some authors have researched the availability of resources as they pertain to farmer participation and soil nutrition. Perlack and Turhollow (2003) suggest 65% of corn stover should remain in fields to sustain proper nutrition. Kerstetter et. al. (2001) give a figure of 75% for wheat straw. Farmer participation rates would be influenced by the perception of importance on soil nutrition, and payments to farmers would reflect the cost of inputs necessary to fulfill lost nutritional value. The values for feedstock availability used in the illustration example are given in Table 12. The metric equivalent of Table 12 is given in Table 13.
Table 12: Feedstock Availability

<table>
<thead>
<tr>
<th>Feedstock (15% moisture, wet basis)</th>
<th>Gross Availability (lbs / acre)</th>
<th>% Harvestable considering soil quality</th>
<th>% Farmer participation</th>
<th>Net availability (lbs / acre)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn stover</td>
<td>8564</td>
<td>35</td>
<td>50</td>
<td>1498</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>6197</td>
<td>25</td>
<td>50</td>
<td>774</td>
</tr>
</tbody>
</table>

Table 13: Feedstock Availability – Metric Units

<table>
<thead>
<tr>
<th>Feedstock (15% moisture, wet basis)</th>
<th>Gross availability (kg / hectare)</th>
<th>% Harvestable considering soil quality</th>
<th>% Farmer Participation</th>
<th>Net availability (kg / hectare)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corn stover</td>
<td>9616</td>
<td>35</td>
<td>50</td>
<td>1683</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>6958</td>
<td>25</td>
<td>50</td>
<td>869</td>
</tr>
</tbody>
</table>

The corn stover values are taken from Perlack & Turhollow (2003). The wheat straw values are from Kerstetter et al. (2001).

This will be measured in units of mass or volume per unit area. Sample values are derived from literature and additional analysis. Data from literature permits development of parameters for feedstock availability based on data for yield, residual requirements for soil nutrition, and farmer participation.

3.2.3 Land Area Limit

This parameter is the maximum area of usable land given by

\[ W_{kt} \]

This parameter is used in equation (2) and is unique to each farm \( k \) and season \( t \).
For actual model implementations this parameter would be determined based on regional land use assessment and a survey of individual farm production. This parameter may be difficult to project beyond a few years because there are many types of risks and incentives that could cause a farming operation to discontinue. Low-yielding seasons, poor market prices, and increasing operating costs could all cause a farming operation to go out of business. On the other hand, the value of the land as real estate may escalate to the point where a farmer would be more profitable by selling the land for a non-agricultural development project. These are common phenomena that may decrease the overall geographical density of a feedstock, thus increasing average transportation costs or driving up demand and price of biomass. Thus the actual determination of this parameter is highly case-specific.

The values of farm land area will be modeled according to Table 14.

<table>
<thead>
<tr>
<th>Farm (k)</th>
<th>Farm area (millions of acres)</th>
<th>Farm area (millions of hectares)</th>
</tr>
</thead>
<tbody>
<tr>
<td>k=1</td>
<td>4</td>
<td>1.62</td>
</tr>
<tr>
<td>k=2</td>
<td>6</td>
<td>2.43</td>
</tr>
</tbody>
</table>

Normally this amount of agricultural land would be distributed over many more than two farms. However, modeling a large number of farms increases the computational complexity of the example beyond practicality.\(^1\) Thus for purposes of simplification, the total acreage is allocated to farms k=1 and k=2 only. This total area was chosen so that the feedstock availability could be larger than the total annual processing capacity of the biorefineries.

\(^1\) This is due to integer programming constraints.
3.3 Product Distribution Data

The product distribution parameters considered in the model are product demand, product revenue, distribution cost, inventory holding cost, and shortage cost.

3.3.1 Product Demand

The parameter for product demand is given by

\[ D_{npj} \]

This parameter is used in equation (13) and is unique to each demand location \( n \), conversion period \( j \), and product \( p \). Ethanol is currently considered the primary biorefinery product. It is assumed that ethanol is consumed primarily by the petroleum industry. Ethanol market demand is generally linked to the demand for gasoline and the petroleum refining infrastructure, since the majority of ethanol demand is blended with gasoline at refineries or terminals. Since gasoline demand is seasonal, the overall network of biorefineries has an ethanol demand parameter that is unique to each period. Other biorefinery products (referred to as co-products) would be produced according to price and demand trends which may or may not track petroleum price and demand. This would depend on whether the particular co-product was a product substitute for some analogous petroleum-derived product. If demand and price for the petroleum analog increased, it could potentially mean that the demand and price for the corresponding biorefinery co-product would increase.

For actual model implementations this parameter would be determined using demand forecasting. Forecasting methods comprise a discipline unto themselves, taking into account historical data and factors for anticipated
product market changes. It is likely that users of this model would include a wide variety demand scenarios for strategic planning purposes. Biorefinery developers would likely employ a marketing department or a team of economists to continually update and test different demand scenarios. Forecasting ethanol demand is particularly challenging because so much of the demand is created by legislative decisions having to do with farm policy and energy security. These policies can change from one election to the next, or even more frequently. However, corn ethanol production capacity is currently increasing rapidly in response to regulatory policy. This implies that at least in the near term, regulatory assumptions can be factored into forecasting approaches with a reasonable level of accuracy.

The values for product demand in the illustration example will be modeled at levels that are smaller than biorefinery production capacity. This creates a scenario where the demand to capacity ratios at the facilities is less than 100%. Although demand growth is expected to outpace ethanol production in the near term, these assumptions are made here to illustrate the possibility of carrying inventory. If demand were always larger than capacity, the value of the inventory variable would always be zero. Base demand levels are given in Table 15.

3.3.2 Product Revenue

The parameter for product revenue is given by,

\[ R_{njp} \]

This parameter is used in equation (18) and is unique to each demand location n, conversion period j, and product p. This will be measured in net present
Table 15: Base Demand Levels

<table>
<thead>
<tr>
<th>Product (p)</th>
<th>Demand Location (n)</th>
<th>Monthly Demands (thousands of gallons)</th>
<th>Monthly Demands (thousands of liters)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>2,500</td>
<td>9,470</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>8,333</td>
<td>31,566</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>5,833</td>
<td>22,096</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>8</td>
<td>32</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>8</td>
<td>32</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>4</td>
<td>16</td>
</tr>
</tbody>
</table>

dollars per unit mass or volume sold, indexed to a common year. Just like product demand, product revenue (price) is also a value that requires modeling and forecasting. Although gasoline prices fluctuate, ethanol price elasticity (relationship between price and demand) may not require that price and demand fluctuate proportionally, or even in the same direction. Thus while methods for forecasting may be similar, there is an important distinction between price and demand.

For actual model implementations this parameter would be determined using an approach similar to that of demand. The values for product base revenues used in the illustration example are given in Table 16.

Table 16: Base Revenue Levels

<table>
<thead>
<tr>
<th>Product (p)</th>
<th>Demand Location (n)</th>
<th>Wholesale Price ($ / gallon)</th>
<th>Wholesale Price ($ / liter)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1.50</td>
<td>0.37</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>1.50</td>
<td>0.37</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>1.50</td>
<td>0.37</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>34.66</td>
<td>9.15</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>35.57</td>
<td>9.39</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>34.27</td>
<td>9.05</td>
</tr>
</tbody>
</table>
These values are derived from Business Week (2006) for ethanol and Lynd & Wyman et. al. (2002) for succinic acid.

### 3.3.3 Distribution Cost

The cost to distribute end product is given by

\[ d_{nip} \]

This parameter is used in equation (22) and is unique to each biorefinery site i, demand location n, conversion period j, and product p. This will be measured in net present dollars per unit mass or volume sold, indexed to a common year.

Distribution costs are primarily a function of shipping costs from biorefinery to demand location and thus unique to each pair of i (biorefinery) and n (demand location). Distribution costs can also fluctuate over time based on fuel costs, labor costs, or other time-based factors. Finally each product may have unique shipping requirements such as purity or safety standards that would also affect shipping costs.

For actual model implementations this parameter would be determined as part of a multiple biorefinery feasibility study. This would need to include a logistical survey of regional demand centers (petroleum refineries and terminals). In some cases, the refinery may pay for shipping costs as an adder to commodity ethanol price but, even so, the cost of the distribution operation would still be taken on by the biorefineries. This cost would be estimated by a marketing or logistics department.

The values of distribution cost for the illustration example are given in Table 17.
Table 17: Product Distribution Costs

<table>
<thead>
<tr>
<th>Distribution Costs</th>
<th>$ / gallon-mile</th>
<th>$ / liter-km</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ethanol</td>
<td>0.00079</td>
<td>0.00021</td>
<td>Via commodity tanker truck</td>
</tr>
<tr>
<td>Succinic acid</td>
<td>0.001</td>
<td>0.00026</td>
<td>Via food quality tanker truck</td>
</tr>
</tbody>
</table>

These values are derived from Anonymous (2006), RSM McGladrey (2006), and Wikepedia (2006). Succinic acid is assumed to be a specialty grade product and thus distribution costs are modeled at food grade cost.

3.3.4 Inventory Holding Cost

The parameter for inventory holding cost is given by

\[ h_{ijp} \]

This parameter is used in equation (23) and is unique to each biorefinery site \( i \), conversion period \( j \), and product \( p \). This will be measured in net present dollars per unit mass or volume stored, indexed to a common year. Product inventories play a key role in the supply chain economics of biorefineries because of the seasonal nature of ethanol production and demand. The cost of feedstock and feedstock storage will need to balance with the cost of holding ethanol inventory in such a way as to meet product demand for the greatest profit. This may mean high or low feedstock shipping from farms, high or low feedstock storage levels, high or low production levels, and high or low ethanol inventory at any particular period in the planning horizon. Inventory holding costs are usually modeled as a flat price per unit of product. This implies that holding large inventory equates to high inventory costs.
For actual model implementations this parameter would be determined by the accounting or logistics department of the biorefinery. Inventory modeling is a mature discipline and is covered as a topic in many industrial engineering resources.

The value of inventory holding cost for the illustration example is modeled as $0.0067 per gallon per month for both products. Rented tank storage capacity is normally considered to be $0.01 per gallon per month while owned tank storage capacity is considered as $0.0033 per gallon per month. (Energy Information Administration, 2006.) Thus the value of $0.0067 is selected as a halfway point. Note that the model does not place a limit on the amount of product held in inventory. However, if realistic parameter sets are chosen, the inventory level should remain within practical levels.

3.3.5 Shortage Cost

The parameter for demand shortage cost is given by

\[ g_{nip} \]

This parameter is used in equation (24) and is unique to each demand location \( n \), conversion period \( j \), and product \( p \). This will be measured in net present dollars per unit mass or volume stored, indexed to a common year. Shortage costs are generally treated as a part of inventory modeling and sample values will be derived based on standard texts and industry data survey. However, it should be noted that shortage costs are very difficult to measure in practice. Shortage costs generally include such things as the cost of fulfilling backorder quantities, the cost of lost future sales, the loss of customer goodwill and satisfaction, and may even extend into problems with a public image of poor customer service or business problems.
In actual model implementations this parameter would be determined by the marketing, sales, or logistics department of the biorefinery. Shortage costs are treated as a part of inventory management. The values for shortage / backorder costs will be modeled as 10 times the inventory holding cost per gallon per month for both products. This value is used in order to exceed the value of the inventory holding cost parameter and to achieve a reasonable level of service to customers. (Muckstadt, 2006.) Setting shortage costs greater than holding costs is an important aspect of inventory models, which prevents inventory levels from becoming impractically large.

### 3.4 Spatial Modeling Considerations

Biorefinery sites, farms, and demand locations in the system are within a geographical region. From a material flow perspective, the system is closed within this region, meaning that the feedstock supply chain and distribution network are entirely defined by the model and parameters. The model formulation permits great flexibility in geographical interpretation of the actual system. For example, each farm “k” represents a farm within the system region. Each site “i” represents a geographical place where a biorefinery could be located. Each demand location “n” is a geographical place where products are ultimately consumed. The locations of each k, i, and n, are completely configurable by the model user. These locations would define all transportation distances as well as the dispersion of farms over the landscape.

As described in section 2.5.1, the concept of siting biorefineries is modeled in a very general way, where the permissible number of biorefineries can be configured however the model user chooses. These choices could reflect many facility siting considerations including regulatory issues, local law,
company policy, agricultural yield, demand location density, and other factors. Thus the permissible biorefinery density may or may not be uniform across the modeling region.

Some potential guidelines for spatial aspects of the modeling framework might be:

1) The region is composed of contiguous non-overlapping identically sized square zones in a grid formation.
2) Each zone can contain no more than one farm.
3) The area of each farm (k) may not exceed the area of the zone that it occupies.
4) The location of each farm is assumed to be the geometric center of its zone.
5) Each zone can contain no more than one biorefinery.
6) Biorefinery sites i, are located in the geometric center of their zones.
7) Each zone can contain no more than one demand location.
8) Demand locations n, are located in the geometric center of their zones.
9) A single zone may contain a biorefinery i, farm k, and demand location n.
10) Although the i, k, and n within a zone are assumed to be at the same geometric location, the distances between them may be modeled as greater than or equal to zero.
11) The density of biorefineries within the region must satisfy biorefinery density requirements, as discussed during model formulation.

Figure 2 depicts some of the potential guidelines just described.
Figure 2: Potential guidelines for spatial assumptions

Zones are contiguous non-overlapping identically sized squares.

The number of biorefineries may be restricted to a particular density, Q_{rmax} within each subregion, r.

Transportation and distribution costs may be modeled based on distances between zones.

Subregions, "r" are 3x3 blocks of zones.

Farm locations "k", site locations "i", and distribution locations "n" are modeled from the geometric center of each zone.
4.0 SAMPLE COMPUTER IMPLEMENTATION AND SOLUTION

4.1 Optimization Software Package and Model Code

The sample computer implementation of the problem will be done in a software package called Xpress-MP, developed by Dash Optimization (2006). This package is designed specifically for large-scale mathematical programming problems in supply chain management, operations, and other business applications. The Xpress optimizer is capable of employing a number of optimization methods, but the present study requires only the primal and dual simplex method, which are covered in any introductory optimization text. The coding language for Xpress-MP very closely resembles typical mathematical programming expressions, including summation and set notations. However, whereas in hand-written program formulations there would be symbols that are less commonly used on a standard keyboard, the language uses English words to perform the functions of specialized symbols. For instance, a typical summation expression could be coded as

\[
\text{forall}(k \text{ in KITCHENS}) \sum(s \text{ in SANDWICHES}) \text{ ham}(s,k)
\]

which might represent a vector for the number of ham sandwiches in each group of sandwiches in each kitchen. Similarly, one could restrict the number of ham sandwiches to be an integer with the code

\[
\text{ham: array(SANDWICHES, KITCHENS) of integer}
\]
which means that “ham” is a vector of variables indexed over the sets sandwiches and kitchens and that the vector is of the variable type “integer”. One could limit the number of ham sandwiches in each kitchen by coding

\[
\text{forall}(k \text{ in KITCHENS}) \sum(s \text{ in SANDWICHES}) \text{ham}(s,k) \leq 3.
\]

Similarly, to make other logical restrictions, one could code

\[
\text{forall}(k \text{ in KITCHENS}) \text{ham}(s,k) + \text{tuna}(s,k) \leq 1
\]

which would prevent there being both ham and tuna sandwiches in the same kitchen, assuming that \(\text{tuna}(s,k)\) was properly declared with the statement

\[
\text{tuna: array(SANDWICHES, KITCHENS) of integer.}
\]

The Xpress-MP programming language is thus quite intuitive. Further information on the language and its application is available from Dash Optimization (Gueret et. al., 2000).

**4.2 Model Validation**

It is important to establish and execute a means for validating the accuracy of the model. This will be done in two ways:

1) Use of a mathematically trivial\(^1\) validation scenario and

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\(^1\)“Trivial” is used in the sense that parameters are set at unrealistic but mathematically useful values for purposes of validating model expressions.
2) Analysis of an illustration example scenario using the realistic parameters described above.¹

The first validation method is used to check the internal consistency of the model itself. Internal consistency refers to the logical accuracy of the equations and the code for the computer implementation. This will be done in the present section. The second validation is employed in order to compare the results of the model to real world system behavior. This will be reserved for section 4.3.2.

The approach for the trivial validation is to assume that all conversion factors are equal to 1 throughout the entire supply chain. This implies that one area unit of land produces one mass unit of feedstock, which produces one volume unit of product. Capacities are modeled as easy to use round values. This removes the complexity of conversion factors to allow traceable flows of materials through the system.

The trivial validation is done using the following assumptions:

1) The agricultural yield is 1 unit mass per unit land area.
2) No decay of feedstock occurs during storage.
3) The conversion yield is one volume unit of product per mass unit of feedstock.
4) The cost and revenue parameters are designed such that total revenues can exceed total costs.
5) The demand profile is constructed so that over the planning horizon, the solution must exhibit product shortages in some periods, while exhibiting product inventories in others.

¹ Neither the model itself nor the validation methods are comprehensive mass-balances in the chemical engineering sense. Rather they are representations of flows and stocks that show some of the key economic relationships of a biorefinery industry supply chain.
6) Total production equals total demand over the planning horizon.
7) Shortage costs exceed inventory costs, which prevents a “do nothing” solution.
8) No initial or ending conditions are placed on feedstock storage or product inventory.

Table 18 shows the important concepts of the trivial validation. First, the flow of material from one variable to the next is from left to right, with the planning periods (months) in chronological order from top to bottom. Note that each period’s amount of harvested land area equals the amount of material harvested in that period.\(^1\) In the feedstock storage column, the values are always the cumulative feedstock material harvested minus the cumulative feedstock processed. This is verified in the columns labeled “Feedstock Storage Validation”. Each mass unit of processed feedstock is converted into one volume unit of product, as shown in the columns, “Feedstock Processing” and “Product Manufacture”. Product inventory is the difference between cumulative production and distribution, as shown in the columns labeled “Inventory Validation”. Product backorder (or shortage) quantities are the difference between cumulative demand and cumulative distribution. This is shown in the columns labeled “Backorder Validation”. This validation exercise demonstrates that the model is internally consistent.

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\(^1\) Although the amount of farmland planted is technically not a variable in the model, it can be derived based on the amount of harvested feedstock and the agricultural yield parameter “\(a_{kl}\)”.

102
### Table 18: Trivial Validation Results

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<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Column 1</th>
<th>Column 2</th>
<th>Column 3</th>
<th>Column 4</th>
<th>Column 5</th>
<th>Column 6</th>
<th>Column 7</th>
<th>Column 8</th>
<th>Column 9</th>
<th>Column 10</th>
<th>Column 11</th>
<th>Column 12</th>
<th>Column 13</th>
<th>Column 14</th>
</tr>
</thead>
<tbody>
<tr>
<td>$x_{s,k,m,l}(a)$</td>
<td>$F_s(x_{s})$</td>
<td>$x_{s,k,m,l,p}(a)$</td>
<td>$E_s(x_{s})$</td>
<td>$z_{s,k,l,p}(a)$</td>
<td>$N_{s,k,l}(a)$</td>
<td>$D_{s,k,l}(a)$</td>
<td>$E_{s,x} - Ex$</td>
<td>$E_{s,x} - Ex$</td>
<td>$E_{s,x}$</td>
<td>$E_{s,x}$</td>
<td>$E_{s,x}$</td>
<td>$E_{s,x}$</td>
<td></td>
</tr>
</tbody>
</table>

- $x_{s,k,m,l}(a)$ represents the feedstock harvest and shipment for period $s$.
- $F_s(x_{s})$ represents the feedstock storage for period $s$.
- $x_{s,k,m,l,p}(a)$ represents the feedstock processing for period $s$.
- $E_s(x_{s})$ represents the product manufacture for period $s$.
- $z_{s,k,l,p}(a)$ represents the product inventory for period $s$.
- $N_{s,k,l}(a)$ represents the product distribution for period $s$.
- $D_{s,k,l}(a)$ represents the cumulative demand for period $s$.
- $E_{s,x} - Ex$ represents the backorder validation for period $s$.
- $E_{s,x} - Ex$ represents the inventory validation for period $s$.
- $E_{s,x}$ represents the backorder validation for period $s$.
4.3 Solution to Implementation Example and Analysis

The assumptions used in the implementation example include the parameter values described throughout section 3. Other system assumptions are given in Table 19.

<table>
<thead>
<tr>
<th>Component Set Type</th>
<th>Number of components in set</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>Farms</td>
<td>2*</td>
<td>Farms are non-overlapping (see below).</td>
</tr>
<tr>
<td>Feedstocks</td>
<td>2</td>
<td>Feedstocks are corn stover and wheat straw.</td>
</tr>
<tr>
<td>Biorefineries</td>
<td>3</td>
<td>Biorefineries are dispersed over system region (see below).</td>
</tr>
<tr>
<td>Products</td>
<td>2</td>
<td>Ethanol and succinic acid.</td>
</tr>
<tr>
<td>Demand Locations</td>
<td>3</td>
<td>Demand locations are dispersed over system region (see below).</td>
</tr>
<tr>
<td>Periods</td>
<td>48</td>
<td>Periods are modeled as months, totaling a 4-year planning horizon.</td>
</tr>
</tbody>
</table>

*Two very large farms are used in order to simplify the analysis.

The model output is described here in a top-down fashion, beginning with the high-level economics and progressing through the monthly operational behaviors for the components of the supply chain, including farms, biorefineries, and distribution operations.
### 4.3.1 High Level Economic Results

The model solution consists of a final objective value and final variable values. The objective of the model is net income, or total revenues minus all costs. Figure 3 gives the total revenue, costs, and net income.

<table>
<thead>
<tr>
<th>Line Item Number</th>
<th>Item</th>
<th>Value (in $1000’s except for %)</th>
<th>% of Variable Costs</th>
<th>% of Total Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Total Revenue</td>
<td>$ 1,080,580</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Fixed Startup Costs</td>
<td>$ 368,087</td>
<td>0%</td>
<td>41.6%</td>
</tr>
<tr>
<td></td>
<td>Variable Costs</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Var. Feedstock Costs</td>
<td>$ 299,614</td>
<td>57.8%</td>
<td>33.8%</td>
</tr>
<tr>
<td>4</td>
<td>Var. Conversion Costs</td>
<td>$ 201,871</td>
<td>39.0%</td>
<td>22.8%</td>
</tr>
<tr>
<td>5</td>
<td>Var. Distribution Costs</td>
<td>$ 11,726</td>
<td>2.3%</td>
<td>1.3%</td>
</tr>
<tr>
<td>6</td>
<td>Var. Inventory Costs</td>
<td>$ 4,715</td>
<td>0.9%</td>
<td>0.5%</td>
</tr>
<tr>
<td>7</td>
<td>Var. Shortage Costs</td>
<td>$ 0</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>8</td>
<td>Total Variable Costs</td>
<td>$ 517,925</td>
<td>100.0%</td>
<td>100%</td>
</tr>
<tr>
<td>9</td>
<td>Net Income (Objective Value)</td>
<td>$ 194,564</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>% Return on Total Cost</td>
<td>22%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Net Income (Calculated(^1))</td>
<td>$ 194,568</td>
<td></td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Error in Net Income(^2)</td>
<td>$ 4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>% Error in Net Income(^3)</td>
<td>0.002%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Note: Shaded values vary directly with activity in the model. All other cells are either fixed or calculated based on shaded cells. Fixed costs are typically not included in mathematical programs, but are shown here for purposes of comparison.

1) Line 1 minus line 2 minus line 8.
2) Line 11 minus line 9.
3) Line 12 as % of line 11.

Figure 3: Objective value and economic outcome from example implementation
Although in actual implementations the model parameters would be designed to incorporate discounted cash flows, for the sake of simplicity, the example solution and cost analysis in Figure 3 consider the sum of nominal cash flows rather than the discounted total present value of the flows. Total revenue is for the three biorefineries over the four year horizon. Note that the project startup costs (line 2) are the largest portion of the cost, at 42% of total cost.¹ Lynd & Wyman et. al. estimate capital recovery costs as high as 47%. Aden et. al. describe a number of different financing methods for biorefineries, admitting that capital costs could be estimated in a relatively wide range.

Resulting feedstock costs make up 33.8% of total cost. This is in line with Lynd & Wyman et. al. at 31.3% and Aden et. al. at 31.4%.

Model output for conversion costs is 22.8% of total cost. Lynd & Wyman et. al. and Aden et. al. estimate 21.5% and 31.3%, respectively.

Model output for distribution and inventory costs are 1.3% and 0.5%, respectively. These cost components are not expressly mentioned in the Lynd & Wyman et. al. or Aden et. al. studies. Similarly, these studies do not model shortage or backorder costs, which are zero in the model output. Return on total cost, which can roughly be compared to return on investment, is 22% in the model output. This compares to an Aden et. al. value of 24%. Although the comparison of model output to these other studies is representative, it should be noted that the inventory, distribution, and shortage components are not included in the other studies. Thus the studies can not be directly compared. This

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¹ It is worthy to note that fixed costs, such as the cost of capital depreciation or startup cost, are not normally included in mathematical programs because they have no bearing on the optimal solution values and may decrease the performance of the algorithm’s computer execution. Although they do factor into the overall economics of the system and can be considered along with the final objective value, fixed costs do not vary with the flows of materials through the system. They are included in the analysis for comparative purposes only.
further illustrates how the literature tends to not model the biorefinery supply chain, rather just the biorefinery facility itself. Although based on the output it could be argued that inventory costs and distribution costs are not of great concern, the analysis to follow will show how these parts of the system are very important to decision making. Line items 12 and 13 in Figure 3 are the experimental error between the model solution and the calculated results. Theoretically, net income on line 9 should match net income on line 11. This small delta can be attributed to the algorithmic solution procedures used by the software application. No rounding has been applied to the model output. Similar small algorithm related errors also occur in the analysis to follow and will be addressed further there.

4.3.2 Validation of Example Solution

It is important to confirm that the validity of the model applies to the realistic example in addition to the trivial example as presented in section 4.2. Table 20 shows this validation for the realistic example in a format similar that of the trivial example by showing the values of the system variables in each period.

The planning horizon spans 48 months, starting with January of the first year (period 1). The parameters in the first year of the horizon require special treatment in order to properly initialize the model. Periods 1 through 6 exhibit no harvesting or production activity. This is by design, because the first harvestin the horizon is a wheat straw harvest, occurring in periods 7 and 8. In

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1 Recall that wheat straw is harvested in July and August while corn stover is harvested in October and November. The corresponding planting months for wheat are September and October and the corresponding planting months for corn are March and April.
<table>
<thead>
<tr>
<th>Period</th>
<th>Forward Storage (1000's of hectares)</th>
<th>Cumulative Feedstock (1000's of tonnes)</th>
<th>Cumulative Product Demand (1000's of Liters)</th>
<th>Cumulative Product Inventory Validation (1000's of Liters)</th>
<th>Inventory Validation Shortage (1000's of Liters)</th>
<th>Farmland (1000's of Hectares)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Entire</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
order to properly initialize this wheat straw harvest, the parameters allow this wheat to be planted in period 1 (January). In reality, the wheat plantings would have occurred prior to the start of the planning horizon. Initial product inventory levels are held in periods 1 through 6 to demonstrate the capability of the model to carry inventory in periods prior to actual production. But in periods 1 through 6, there are no product demand requirements. This prevents a distorted product demand shortage from occurring in those periods. Technically, demand requirements could have been met if initial product inventory were large enough, but no true production would have occurred until period 7 and initial inventory would have had to be abnormally large. Although initial product inventory can be handled, initialization is not possible with the feedstock storage variable since feedstock storage is strictly defined as the difference between what is harvested and what is processed. Note that no harvests may occur in period 1. However, if the planning horizon began with a harvesting period, such as period 7 (July), instead of period 1 (January), this feedstock storage initialization would be possible. But in this example, the period numbers are assigned to their respective months to simplify the interpretation of the results. The initialization year affects the total system cost in two ways. First, the initial inventory in periods 1 through 6 carries a cost, which is quite small in relation to the overall costs. Second, the fixed startup costs given in Figure 3 are for the entire 48 month horizon. If the fixed costs for periods 1 through 6 were not included in the analysis, this would reduce the fixed costs by approximately $46 million. But again, although this is a large cost affecting the overall economic outcome, the fixed costs do not impact the values of the optimal decision variables. Aside from these two points, the model does not incur any operating costs in periods 1 through 6.
The Farmland Use column is derived from the the Feedstock Harvest variable simply for reference, and is not a variable in the model. Note that the hectares of farmland use per mass of feedstock harvested will vary depending on agricultural yield. If yield variability were included in the model parameters, it would also affect this number. To verify that these relationships are correct, observe period 7, where the harvest consists entirely of wheat straw. Here the agricultural yield corresponds to approximately 870 kg of wheat straw per hectare of land, which is what we see in Table 13. Similarly, in period 10, we observe a corn yield of 1,682 kg per hectare, also corresponding to the values in Table 13.

The feedstock storage quantities are validated in the columns labeled “Feedstock Storage Validation”. These show the net difference between cumulative feedstock harvested and feedstock processed, and the absolute error with the Feedstock Storage column. These errors are on the order of 0.0001% error and show as zeroes. They can be attributed to the precision of the algorithm execution.

To validate material conversion, we observe the relationship between the Product Manufacture variable and the Feedstock Processing variable. Note that in period 8, we observe a conversion yield of 0.318 Liters of ethanol per kilogram of wheat straw processed. This period in particular converts only wheat into only ethanol. But other periods may involve processing both feedstocks to produce both ethanol and succinic acid, which would make the overall product yield different for different periods in Table 20. Furthermore, this conversion yield could vary based on quality of material by farm, or the length of time the material had been stored. The latter consideration is
incorporated in the model parameters. This will be explored graphically later in the paper.

The product inventory quantities are validated in the columns labeled “Inventory Validation”. These show the net difference between cumulative product manufactured and cumulative product distributed plus initial inventory, as well as the absolute error with the Product Inventory column. These errors are on the order of 0.0001% error and show as zeroes. They can be attributed to the precision of the algorithm execution.

The product distribution quantities exactly match the demand in each period, which leads to zero shortage in each period. This was possible because there was always enough inventory on hand to meet demand. The trivial example illustrated what happens when this is not the case, namely that product shortages are accumulated and production must continue until cumulative demand is met.

It is important to recognize that this has been an aggregate validation, where the material quantities for both farms, both feedstocks, all three biorefineries, both products, and all three demand locations are summed together. Since the sums are accurate, the individual material flows are accurate. The remaining graphical analysis of the model solution examines the individual system components and their relationships to one another.

4.3.3 Analysis of Individual System Components

While the validation in section 4.3.2 presented the aggregate model solution outcome, the model also permits the analysis of the individual farms, feedstocks, biorefineries, products, and demand locations. The distinctive characteristics of each of these components, which are defined by the
parameters, influence the model output. These characteristics include total farm area, manufacturing capacity, and the proximities between farms, biorefineries, and demand locations. In other words, the farm acreage is unique to each farm, the manufacturing capacity is unique to each biorefinery, and so on. Other key aspects of uniqueness are the feedstock transportation and product distribution distances used in the example. These are given in Tables 21 and 22, respectively.

Table 21

<table>
<thead>
<tr>
<th>Farm k</th>
<th>Site i</th>
<th>distance from k to i (miles)</th>
<th>distance from k to i (kilometers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>45</td>
<td>72</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>101</td>
<td>162</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>101</td>
<td>162</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>64</td>
<td>102</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>90</td>
<td>144</td>
</tr>
</tbody>
</table>

Table 22

<table>
<thead>
<tr>
<th>Site i</th>
<th>Demand Location n</th>
<th>distance from i to n (miles)</th>
<th>distance from i to n (kilometers)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>20</td>
<td>32</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>3</td>
<td>20</td>
<td>32</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>45</td>
<td>72</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>28</td>
<td>45</td>
</tr>
<tr>
<td>2</td>
<td>3</td>
<td>20</td>
<td>32</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>45</td>
<td>72</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>40</td>
<td>64</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>45</td>
<td>72</td>
</tr>
</tbody>
</table>
Other system characteristics could be modeled differently among the various components, but are modeled as identical in the present example. These include agricultural yields (modeled as identical among farms), product conversion yields (modeled as identical among biorefineries), and product prices (modeled as constant for all products in all periods).

4.3.3.1 Feedstock Harvest Results

The amount of farmland harvested over the planning horizon is depicted in Figure 4. These results are a derivation from the feedstock harvest variable. This depicts the breakdown of land area harvested by feedstock type. In the first two years of the horizon, both wheat straw and corn stover are harvested. But in the third and fourth years, only wheat straw is harvested. Now consider Figure 5, which shows the corresponding mass of feedstock harvested and shipped over the planning horizon. Clearly this mimics the pattern observed in Figure 4, but the relative agricultural yields between the two feedstocks cause corn stover mass to be more well represented here than in Figure 4. The results further show that the amount of wheat straw shipped is considerably larger than corn stover for the planning horizon overall. This suggests that wheat straw is economically preferable to corn stover. To examine this, we combine information from Table 5 and Table 9. Table 5 shows that corn stover conversion yield to ethanol is 374 liters per tonne, while wheat straw conversion to ethanol is only 319 liters per tonne. But factoring in the respective feedstock costs from Table 9 shows that the ethanol produced per dollar spent on corn stover is only 13.5 liters per dollar, whereas with wheat straw, the ethanol produced is 17.8 liters per dollar. Thus the tendency towards processing wheat
Figure 4: Farmland Harvested by Feedstock

Figure 5: Feedstock Harvested & Shipped by Feedstock Type
straw over corn stover is reasonable, all other aspects being equal.\(^1\) The discussion of the large wheat harvest in period 32 is reserved for later in this section, since we must look deeper into the results for the explanation.

Now observe Figure 6, which shows the breakdown of each farmer’s contribution to the corn stover production. This shows that farm \(k=2\) produces most of the corn stover. Now observe the profile for wheat straw in Figure 7. This shows that the wheat production is shared between the two farms, with a significant preference for farm \(k=2\). Figures 6 and 7 suggest that farm \(k=2\) is economically preferred and that farm \(k=1\) is used primarily to help meet the peak feedstock demand times. This makes sense intuitively, because Table 21 indicates that farm \(k=2\) is closer than \(k=1\) to all biorefinery sites.

Next we examine where the feedstocks are shipped. Figure 8 displays the corn stover shipments from farm \(k=2\) by biorefinery site destination. This reveals that farm \(k=2\) supplies its corn stover to all three biorefinery sites, with a majority going to biorefinery site \(i=2\). Now consider the corn stover shipments from farm \(k=1\), as shown in Figure 9. This indicates that a majority of the corn stover from farm \(k=1\) is supplied to biorefinery site \(i=3\). Remember that Figure 6 shows that period 10 (October of first year) is the only corn stover harvest from farm \(k=1\).

Next observe the wheat straw shipments from the farms by biorefinery destination in Figures 10 and 11. Again notice that farm \(k=2\) tends to ship wheat straw to all 3 locations while farm \(k=1\) ships mostly to biorefinery site \(i=3\). The propensity for farm \(k=1\) to ship to site \(i=3\) again has to do with proximities between components within the supply chain. As mentioned

\(^1\) The comparison assumes that both feedstocks are used in the same period they are harvested (no decay) and that transportation is 1 kilometer (same distance).
Figure 6: Corn stover harvested & shipped by farm of origin

Figure 7: Wheat straw harvested & shipped by farm of origin
Figure 8: Corn stover shipped from farm k=2 by destination

Figure 9: Corn stover shipped from farm k=1 by destination
before, Table 21 indicates that farm $k=1$ is further than $k=2$ from all three biorefineries. But according to Table 22, biorefinery site $i=3$ also happens to be farthest from all three demand locations ($n=1, 2, \text{and } 3$). This means that products from biorefinery site $i=3$ that were made from feedstocks at farm $k=1$ would be the most expensive from a transportation perspective, since that pathway was “longest” in terms of kilometers from the farm to the demand location. Thus a preferable situation would be to supply feedstocks from farm $k=2$ to biorefinery sites $i=1$ and $i=2$, for eventual distribution of products to demand locations $n=1, 2, \text{and } 3$.

4.3.3.2 Feedstock Storage Results

The feedstock storage profile is impacted by availability of feedstocks from harvest and from product demand. Observe this profile for the system overall by feedstock type in Figure 12. This profile illustrates the seasonal use and replenishment of the feedstocks. Period 7 is the first allowable harvest period for wheat straw, while period 10 is the first harvest for corn stover. Corn stover is replenished in the first and second year (in periods 10-11 and periods 22-23), while wheat straw is replenished in all four years of the horizon. These results are easily compared with Figure 5, which show the harvested amounts by feedstock. Note that the peak feedstock storage level in period 32 coincides with the peak harvest period in Figure 5. To explain this, we continue the analysis.

Figures 13, 14, and 15 compare the feedstock storage profiles by feedstock for the biorefineries at sites $i=1, \ i=2, \text{and } i=3$, respectively. This immediately shows that the feedstock storage profiles for sites $i=1$ and $i=2$ are extremely similar, both in profile shape and amount of feedstock stored. Their
Figure 10: Wheat straw shipped from farm $k=2$ by destination

Figure 11: Wheat straw shipped from farm $k=1$ by destination
respect the proportions of corn stover to wheat straw are also very similar. But site \( i=3 \) is distinctly different. The storage levels are held constant over much of the planning horizon, suggesting that there are some periods during which no feedstock is used. To investigate this further, we must observe the results for the feedstock processing variable, \( x_{iklmj} \).

### 4.3.3.3 Feedstock Processing Results

Figure 16 displays the feedstock utilization at biorefinery site \( i=3 \) by feedstock type. Now compare Figures 15 and 16. The “plateaus” where feedstock storage levels remain constant in Figure 15 correspond closely to those periods where, according to Figure 16, no feedstock is processed. Note that it is possible for feedstock levels to remain constant from one period to the
Figure 13: Feedstock storage at site i=1 by feedstock type

Figure 14: Feedstock storage at site i=2 by feedstock type
Figure 15: Feedstock storage at site i=3 by feedstock type

Figure 16: Feedstock processed at biorefinery site i=3 by feedstock
next if the first of the two periods happens to be a harvest period. This is evidenced between periods 7 and 8, as well as between periods 8 and 9.

Now let us observe feedstock utilization for the system as a whole. Figure 17 displays the feedstock processing results for the entire system by feedstock type. Unlike Figure 16, Figure 17 shows that feedstock is processed in every period (except for the initialization periods 1-6). Period 24 is the only period in which both feedstock types are processed. This suggests that in general, each period has a respective economical “feedstock of choice”. Notice the timing of wheat straw use versus corn stover use. Once corn stover becomes available in periods 10 and 11, it is used exclusively until the next wheat straw harvest in period 19. Wheat straw is then used again until the period 22 corn stover harvest (October of second year). Just as the total system
Figure 18: Total feedstock processed by biorefinery

Figure 19: Total product manufacture by biorefinery
harvest in Figure 5 shows an economic preference for wheat straw in the third and fourth years of the planning horizon, so does Figure 17 show this preference.

Next we examine the amount of total feedstock processed by biorefinery in Figure 18. These results follow from the earlier discussion of biorefinery site \( i=3 \) being less economically preferred than sites \( i=1 \) and \( i=2 \). Feedstock utilization is constant across all periods for the biorefineries at sites \( i=1 \) and \( i=2 \). But site \( i=3 \) processes feedstocks only when necessary to meet demand requirements. Note that the feedstock processing levels at biorefinery sites \( i=1 \), \( i=2 \), and \( i=3 \) are approximately 61,000; 76,000; and 101,000 tonnes per month, respectively, when processing occurs.

4.3.3.4 Product Manufacturing Results

Figure 19 shows all product manufacturing by biorefinery. The shapes of the production profiles here are very similar to the profiles for feedstock processing in Figure 18, except that there are minor declines in production quantities from one period to the next starting with each harvest period. This is caused by the decrease in feedstock quality due to material decay during storage. The longer the feedstocks are stored, the lower the product conversion yields. According to Table 6, corn stover decays at a greater rate than wheat straw, thus the more distinctive decrease of product manufactured in periods 11 through 19 and periods 23 through 30. Figure 20 displays total manufacturing by product. Note that the amount of succinic acid produced (\( p=2 \)) is extremely small compared to ethanol production. This is due to much lower demand.
Figure 20: Total manufacturing by product

Figure 21: Succinic acid manufacturing by biorefinery
Observe Figure 21 for a closer look at the production of succinic acid. Succinic acid is only manufactured in periods 7, 10, and 22, and is produced primarily by site \( i=3 \). Although it appears from Figure 21 that biorefinery site \( i=1 \) is not represented, Figure 22 shows that there is a very small amount of succinic acid produced there in order to fulfill the ending inventory requirement. Ending inventory requirements will be discussed in the following session.

![Succinic Acid Manufacture at Biorefinery Site i=1](image)

Figure 22: Succinic acid manufacturing at biorefinery site \( i=1 \)

4.3.3.5 Product Inventory Results

The overall product inventory storage profile by biorefinery is depicted in Figure 23. This profile clearly displays the effect of initializing the model with product inventory at the beginning of the planning horizon. Periods 1 through 6 have no demand requirements, so the initial inventory is held
constant during this time. Starting with period 7, the harvests begin and demand requirements continue through period 48. Notice that sites $i=1$ and $i=2$ hold relatively low inventories compared to site $i=3$. Since inventory carrying costs are the same at each facility, it is no less economical to keep inventory at site $i=3$ than at the other two sites. So the intermittent production at $i=3$ is held in inventory and used to “shave” the demand only when the other two sites cannot meet demand. Also compare the inventory profile of Figure 23 with the total system harvest in Figure 5 and the total system feedstock storage profile in Figure 12. Notice that the peak feedstock level in period 32 does not translate through to a corresponding product inventory peak. Rather this feedstock peak is merely a replenishment of raw material that is used to maintain the seasonal product inventory pattern observed from year to year in Figure 23.
feedstock peak also results from a necessarily large wheat straw harvest. Since wheat straw does not yield as much finished product, and since all three biorefineries must procure a large amount of wheat straw simultaneously, a large amount of wheat straw is needed. Thus the seemingly abnormal feedstock peak in period 32 is attributed to the seasonal product inventory pattern and the simultaneous need for wheat straw at all three biorefineries. Furthermore, since wheat straw is economically preferred over corn stover, the system only uses corn stover when it must build product inventory to meet demand, final feedstock storage requirements, or final product inventory requirements. The reason the system is forced to use corn stover at all is that the processing capacity is constrained. Corn stover yields more product upon conversion, so to accommodate the product inventory pattern and product demand requirements in the first and second years without exceeding total system processing capacity in any one period, corn stover must be used. It may seem that this could be overcome by harvesting only wheat straw and forcing biorefinery i=3 to produce more product, but the optimal economic solution to the model would indicate otherwise.¹

The final inventory and feedstock storage requirements impact the results because without these requirements, the optimal solution would have resulted in zero feedstock storage and zero inventory in the final period since that would have decreased the overall cost. These requirements are put in place to generate a more steady-state view of what the solution would look like if the horizon were to extend further into the future.

¹ The discussion in this section is an example of how the supply chain modeling approach reveals aspects of biorefineries that would otherwise not be considered in technical facility design studies.
Figure 24 shows the inventory profile for succinic acid, which makes up only a very small part of the inventory profile in Figure 23. This inventory profile displays a very uniform inventory reduction for succinic acid. This figure corresponds directly to the production shown in Figure 21. Notice that there is a small amount of initial inventory held in periods 1 through 6. As mentioned earlier, the succinic acid production at biorefinery site $i=1$ is merely to meet final inventory requirements, and is not distributed to demand locations at all. This is shown in Figure 25. This also shows the initial inventory of succinic acid biorefinery site $i=1$ which is consumed in period 8.

4.3.3.6 Product Distribution Results

Product distribution by demand location is shown in Figure 26. This shows that product demand is met in every period, leaving no shortages in any period. Zero shortages correctly imply that there is a significant economic disincentive to incur shortage costs. This is the effect of the values for the shortage cost parameter, as discussed in section 3.3.5. Recall that there are no demand requirements for periods 1 through 6. Figures 27, 28, and 29 display product distribution by biorefinery for demand locations, $n=1$, $n=2$, and $n=3$ respectively. These clearly shows that demand location $n=1$ procures products from only biorefinery site $i=3$. Demand location $n=3$ procures products from only site $i=2$, while demand location $n=2$ receives products from all three biorefineries.¹ As mentioned earlier, these preferential relationships are caused by the relative proximities among the biorefinery sites and demand locations.

¹ The underlying data confirm that this is true for both ethanol and succinic acid.
**Figure 24:** Succinic acid inventory by biorefinery site

**Figure 25:** Succinic acid inventory at biorefinery site $i=1$
Figure 26: Product distribution by demand location

Figure 27: Product distribution by biorefinery site for demand location n=1
Figure 28: Product distribution by biorefinery site for demand location n=2

Figure 29: Product distribution by biorefinery site for demand location n=3
4.3.4 Dual Solution

Feasible optimal solutions to mathematical programs have what are referred to as “dual solutions”. Thus far, only the regular solution or “primal solution” has been discussed. The primal solution provides the optimal values of the decision variables, such as “y”, the amount of feedstock harvested, or “E”, the amount of product manufactured. But the dual solution is an extended interpretation of the primal solution that gives very useful economic information about the system. The “theory of duality” is covered as a fundamental topic in mathematical programming texts. The essential concept of duality is that the economic value of constrained resources can be determined. For example, assume that the biorefinery supply chain system only had access to a limited amount of harvestable land. How much more profit might be made if the system had access to more land? Or suppose that the system would be more profitable if one of the biorefineries had additional production capacity in a particular period. How much more profit could be generated for that biorefinery in that period? This kind of economic information is exactly what the dual solution provides. Each constraint expression in a mathematical program is associated with exactly one dual variable, which gives the economic value of an additional unit of a constrained resource, such as an acre of land or a gallon of production capacity. Thus the biorefinery supply chain model is capable of producing such information. Table 23 gives illustrative dual variable values for the example solution. This demonstrates how the model can be used to assess the value of various resources at various times over the planning period. Such information could be
Table 23: Dual Variable Examples for Processing Capacity, $f_{0ij}$

<table>
<thead>
<tr>
<th>Constrained Resource</th>
<th>Dual Variable (Constraint)</th>
<th>Index Information</th>
<th>Economic Value per Unit Constrained Resource ($/ kg processing capacity)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing Capacity</td>
<td>$f_0^1$</td>
<td>Site $i=1$</td>
<td>0.020</td>
</tr>
<tr>
<td>Processing Capacity</td>
<td>$f_0^1$</td>
<td>Period $j=48$</td>
<td></td>
</tr>
<tr>
<td>Processing Capacity</td>
<td>$f_0^2$</td>
<td>Site $i=2$</td>
<td>0.012</td>
</tr>
<tr>
<td>Processing Capacity</td>
<td>$f_0^2$</td>
<td>Period $j=44$</td>
<td></td>
</tr>
</tbody>
</table>

used to identify system bottlenecks or opportunities for additional profit. Note that often the value of dual variables is zero, meaning that an increase in a resource does not improve the profitability of the system. In such cases, the resources are not strictly “constrained”. Rather they are “slack”. Dual solutions might be used to explore questions about the value of land at specific times in the planning horizon, the capacity of biorefineries, or the value of one feedstock or end product over another.
5.0 DISCUSSION

5.1 Achievement of Objectives and Comparison to Literature

The objectives of the research are to “establish a dynamic modeling framework for a biorefinery supply chain system and to illustrate the use of that framework by example.” The presentation of the model formulation, validation, example solution, and solution analysis have demonstrated that the model provides a framework for evaluating the economic outcomes and system flows of a biorefinery supply chain. The modeling framework facilitates a mathematical optimization of agricultural and manufacturing decisions to achieve maximum profitability. If applied to actual systems, the model would aid strategic planning and decision making.

The seven key questions presented in section 1.2.1 and revisited with the objectives are directly addressed by the modeling framework, because the decision variables in the model are specifically designed to answer these questions. The feedstock harvesting variable (y) provides information about the feedstock quantities required for processing over the course of the planning horizon. This variable can also be used to derive the land area requirements for the system. The storage variable (Fs) provides information regarding quantity and duration of storage. The discussion of useful model extensions in section 2.5 describes the model formulation required to answer questions 4 and 7, relating to the initial location and capacity of biorefineries and their capacity increases over time. While for the sake of practical implementation this was not presented as part of the example solution, the model could be implemented to include these factors. The feedstock procession variable (x) and product
manufacture variable (E) aid decision making for scheduling when and how much product to make. And the inventory (In) and distribution (z) variables evaluate the distribution of products.

As found in the literature review, many separate aspects of biorefinery supply chain modeling have been explored, sometimes in significant depth. However, there is no one study that seems to incorporate a holistic system like the modeling framework here. The important aspects integrated are:

1) Consideration of harvesting and storage of multiple feedstock types over a seasonal planning horizon.
2) Multiple feedstock source locations (farms).
3) Non-uniform levels of feedstock processing and product manufacturing over a seasonal planning horizon.
4) Consideration of multiple biorefineries operating in a common region sharing feedstock resources and customers.
5) Inclusion of multiple product types (co-products).
6) Inclusion of dynamic inventory and shortage models for multiple biorefineries and demand locations.
7) Inclusion of product demand and distribution as part of the system.
8) Volatility of product price and demand.
9) Inclusion of transportation distances as being to and from specific locations instead of being “average” distances around a single biorefinery.
10) Use of a periodic planning horizon instead of annual static assumptions.
5.2 Scenarios

The validations and results presented in section 4.0 demonstrate the accuracy and usefulness of the model. The graphical analysis demonstrated the many ways in which the model could be used to guide strategic planning and decision making. A biorefining enterprise or policymaking body could implement this mathematical decision model under many different scenarios to guide many kinds of strategic decisions. This would be done by changing the parameter set to reflect the desired real world scenario, executing the model under that parameter set, and carrying out an analysis as just presented. The scenarios could be designed to test a wide variety of hypotheses, and the Xpress-MP software could be further utilized to conduct sensitivity analyses on the values and assumptions in the parameter set.

There are potentially many kinds of scenarios and hypotheses that could be tested using the model. Implementations might include a “base case” scenario and several other scenarios. The base case would be that set of parameters that would result from the research of subject matter experts. Other scenarios might be slight thematic variations on the base case. Possible scenarios might include variations as described in the following sections.

5.2.1 Biorefinery Variations

The biorefinery parameters could be varied to generate scenarios that represent such considerations as

1) Single feedstock operations versus multi-feedstock operations,
2) Large versus small minimum and maximum allowable annual production capacities,
3) High versus low feedstock costs,
4) High versus low volatility of feedstock costs,
5) High versus low volatility in conversion efficiencies for each feedstock,
6) High variation in the conversion efficiencies among feedstocks,
7) High versus low values for investment, operation, and maintenance,
8) Constraining the distances between biorefineries,
9) Allowing high versus low biorefinery densities.

5.2.2 Agricultural Variations

One could also vary the agricultural parameters to generate scenarios that represent such considerations as
1) different numbers of feedstocks,
2) high and low volatility in farmer participation rates among farmers over time,
3) high and low variation in feedstock yields among farms in the region,
4) monocropping versus polycropping within a given time horizon,

5.2.3 Distribution Variations

The distribution parameters could be varied to generate scenarios that represent such considerations as
1) high and low transportation costs,
2) high and low demand,
3) volatile versus stable demand,
4) high and low product prices,
5) high and low costs of inventory storage,
6) high and low shortage costs,
7) varying the pricing schemes in close correlation with gasoline or other commodity demand.

These considerations alone already lead to a very large number of possible parameter combinations for scenarios. An actual implementation would lead to a final set of scenarios to be used in the analysis that will be used to compare the scenario outcomes and compare the relative merits of each.

5.3 Hypotheses

5.3.1 Biorefinery Hypotheses

A key hypothesis for biorefineries is that it is economically preferable to have all biorefineries capable of processing all feedstock types. Though on the contrary, it may be that costs could be minimized if only one feedstock were permitted for the whole system, or if each biorefinery specialized in using one of the possible feedstocks. This hypothesis will depend heavily on the agricultural parameters for the region. If the crops are uniformly distributed throughout the region, this would likely support the claim. Alternatively, if certain pockets of the region had high yields in a single feedstock and lower yields in others, then the claim might not hold.

It may be hypothetically beneficial to have smaller more distributed biorefineries in the region rather than large, centralized ones. Of course, if the economies of scale for large plants overcome the benefits of reduced transportation costs, then this hypothesis might not hold.

Finally, one could hypothesize that having the capability to produce ethanol from multiple feedstocks would make it less expensive to effectively meet volatile ethanol demand patterns. This is because having harvest windows more evenly spread over time would decrease the need for large storage
inventories. Since smaller storage inventories might reduce the gap between the amount of material stored and the amount of material needed over the time periods, storage costs and losses to decompositions would be minimized, thus optimizing profit. This hypothesis could be untrue since it could mean that there would be underutilized conversion capacity, resulting in high cost. This might instead result in a net outcome that favored large inventories in times of volatile ethanol demand.

5.3.2 Agricultural Hypotheses

It is reasonable to hypothesize that a greater number of available feedstocks would help to smooth feedstock cost variability. A diversified supply of materials could mean that decision makers could always choose the lowest cost option in any given period. Not only does this help to manage volatility, but keeps costs low in general, thus improving the optimal solution. However, this hypothesis could be disproved if the costs of switching feedstocks from period to period are too high, or if the lowest cost feedstocks have poor ethanol conversion factors. Other hypotheses can be formed based on farmer participation, yield, and decomposition rates, but the potential variations in agricultural parameters essentially reduce to variations in availability and cost.

5.3.3 Distribution Hypotheses

A hypothesis for distribution might be that increasing transportation cost would bring the location of the biorefineries closer to the demand locations. Alternatively, lower costs might loosen the proximity of biorefineries to demand locations. Volatility in demand might increase the inventory and
shortage costs if the production at the biorefinery is unable to match the demand trend. This would likely be a function of both biorefinery capacity and feedstock availability combined. If a particular biorefinery product such as ethanol were to track the price or demand for a particular commodity such as gasoline, this may have the effect that the product mix of the biorefineries would vary with that commodity as well.

5.4 Method for Comparative Analysis of Output from Scenarios

The model executions from each scenario would produce solutions that would be directly comparable. The objective values and decision variables would be in identical units over identical indices. Thus the locations of all biorefineries could be directly compared among scenarios. Feedstock cultivation and harvesting levels, biorefinery production levels, and all other variables would be easily and compatibly compared.

The analysis could be taken further, however, to include the sensitivity of the solutions to changes in parameters. By running many optimizations focusing on each parameter or the interplay between a small number of parameters, a decision maker could identify those parameters to which the system is most sensitive. After a small number of scenarios would surface as the “best few”, the analysis might be further extended using simple optimization simulations, whereby key parameter values would be randomly generated and used in model runs in an iterative fashion. With enough iterations, this procedure could produce a very tight confidence interval around the most probable solution values for each of the best few scenarios. Ultimately, the quality of the comparative analysis of scenarios would rely on
well-developed parameter values, thoughtful iterative experimentation, and fast and easy analytical procedures.

5.5 Conclusion and Contribution

This study has described the importance of this research on the national agenda and its current relevance to industry. The literature review presented a number of studies with pertinent objectives and methodologies. This review also cited sources that provide examples for key parameter values or that describe methods for developing parameter values. However, these studies did not fully integrate some of the key aspects of biorefinery supply chain systems. The study has presented a mathematical model to support strategic decision making for biorefinery enterprises. It also described the definition of and collection methods for model parameters. The model was coded into a software package and executed to provide an illustration for use of the model. This was followed by analysis of the solution. A number of business hypotheses were presented that enterprises might test using the mathematical decision model. These outcomes could be used to support strategic decision making.

This original contribution gets at the heart of the feedstock supply chain and product distribution challenges that will need to be addressed as the biorefinery industry develops. It is offered as an important step in bringing the knowledge of biomass resource and technology studies together with the discipline of operations research to focus specifically on the integration of feedstock supply chain and product distribution systems. Although this study does not make statements regarding real world systems or outcomes, it does offer a more complete and credible mathematical modeling framework for biorefinery system strategic planning and decision making than those models
presented in the literature review. This contribution provides a new paradigm for considering biorefinery supply chains with respect to agricultural resource planning, supply chain economics, and net energy studies since assumptions about supply chain must underlie such studies. Finally, this contribution provides a more holistic, interdisciplinary way of planning the biorefinery industry from farm to final product use.
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