

MODELING AND OPTIMIZATION OF BIOFUEL SUPPLY CHAIN CONSIDERING
UNCERTAINTIES, HEDGING STRATEGIES, AND SUSTAINABILITY CONCEPTS

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Modeling and optimization of biofuel supply chain considering uncertainties,
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ABSTRACT

Due to energy crisis and environmental concerns, alternative energy has attracted a lot of attention in both industry and academia. Biofuel is one type of renewable energy that can reduce the reliance on fossil fuel, and also help reduce environmental effect and provide social benefits. However, to deliver a competitive biofuel product requires a robust supply chain. The biofuel supply chain (BSC) consists of raw material sourcing, transporting of raw materials to pre-treatment and biorefinery sites, pre-treating the raw material, biofuel production, and transporting of the produced biofuel to the final demand zones. As uncertainties are involved throughout the supply chain, risks are introduced.

We first propose a stochastic production planning model for a biofuel supply chain under demand and price uncertainties. A stochastic linear programming model is proposed and Benders decomposition (BD) with Monte Carlo simulation technique is applied to solve the proposed model. A case study compares the performance of a deterministic model and the proposed stochastic model. The results indicate that the proposed model obtain higher expected profit than the deterministic model under different uncertainty settings. Sensitivity analyses are performed to gain management insights.

Secondly, a hedging strategy is proposed in a hybrid generation biofuel supply chain (HGBSC). A hedging strategy can purchase corn either through futures or spot, while the ethanol end-product sale is hedged using futures. A two-stage stochastic linear programming method with hedging strategy is proposed, and a Multi-cut Benders Decomposition Algorithm is used to solve the proposed model. Prices of feedstock and ethanol end-products are modeled as a mean reversion (MR). The results for both hedging and non-hedging are compared for profit

realizations, and the hedging is better as compared to non-hedging for smaller profits. Further sensitivity analyses are conducted to provide managerial insights.

Finally, sustainability concepts, which include economic, environmental, and social sustainability, are incorporated in the HGBSC. A two-stage stochastic mixed integer linear programming approach is used, and the proposed HGBSC model is solved using the Lagrangean Relaxation (LR) and Sample Average Approximation (SAA). A representative case study in North Dakota is used for this study.

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DEDICATION

This work is dedicated to the almighty God. With you, all things are possible. God has seen us through. I am extremely grateful for His abundant mercies and peace through this journey.

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CHAPTER 1: BIOFUEL SUPPLY CHAIN UNCERTAINTY, HEDGING, AND SUSTAINABILITY

1.1. Introduction

Due to the increasing demand of energy and environmental concern of fossil fuel, it is becoming extremely important to find other alternative energy sources. Biofuel energy as an alternative and additive form of energy to fossil fuel has gained much attention in recent times. In order to deliver competitive biofuel to the end-market, a robust biofuel supply chain (BSC) is essential. Biofuel supply chain is a complex system which consists of multiple uncertainties such as cost of raw materials, conversion of raw materials into end-products, prices and demand of end-products. These uncertainties if not considered in the decision making process result in non-optimal solutions which generate lower profits or increased costs. This dissertation therefore examines the impact of uncertainties on the performance of the biofuel supply chain by incorporating uncertainties into the decision making process to make optimal decisions such as; the amount of raw materials to buy, amount of end-products to produce, and the production planning schedule to develop. Hedging strategies are subsequently implemented to hedge against these uncertainties/risks in the biofuel supply chain setting. Additionally, many supply chain models that have been developed do not integrate the entire sustainability concepts such as economic, environmental and social issues. This research provides a framework that incorporates these concepts in the model developed. Overall, this research outcome will help to design a robust biofuel supply chain towards sustainability in order to utilize the renewable biofuel in the near future. The findings can be used by the bioenergy industries in USA, especially North

Dakota to operate efficiently and effectively and boost economic activities and protect the environment.

1.2. Research background

Today's energy consumption is increasing at a faster rate. Recent studies have shown that mainstream crude oil cannot sustain the volume of worldwide demand and consumption of energy. Renewable energy, specifically biofuel, has gained attention as a competitor and alternative source of energy to crude oil, especially in the transportation sector. In order to ensure a consistent and a competitive supply of these biofuels to the end markets, a reliable and resilient supply chain is needed to help coordinate all the activities and streamline the demand and supply activities. Because uncertainties such as biomass cost, demand and prices of biofuels and by-products, as well as decisions such as the amount of raw materials to purchase and the amount of end-products produced are crucial in the biofuel supply chain management. Literature that has considered the biofuel supply chain has not extensively incorporated uncertainties into the supply chain decision-making process. Most of the applications in the biofuel supply chain have focused on deterministic problems, and assume the demand, price are certain by using mixed integer linear programming (MILP) methods to solve such problems. Decisions based on deterministic assumptions will result in non-optimal (or even impossible) solutions if uncertainties exist. Therefore it is essential to develop an optimization model in the biofuel supply chain system that considers existing uncertainties.

Hedging is essential in the biofuel supply chain as a mechanism to reduce price and demand risks that are inherent in the daily operation. In most cases, derivatives are widely used for hedging to help lock in existing profits by providing a form of stability to the volatility of a portfolio, by reducing the risk. Both financial and operational hedging protects the ethanol

producer from price and demand risks due to market fluctuations as a result of economic, political, and other reasons. The basic rule in hedging is that the risk of loss in portfolio is offset by the gains in the futures or options. Hence hedging is beneficial by locking in prices or cost at favorable returns. Importance of hedging within a hybrid generation biofuel supply chain (HGBSC) setting will be to minimize the impact of profit variation.

Economic decision models that are developed without considering other needs of a society such as environmental and social do not show the practical relevance. Biofuel supply chain models that integrate sustainability provide a better decision making and will forecast realistic profits or costs. This will help in better c-ordination for the activities in the entire supply chain. An economic model which promotes environmental and social needs is crucial for economic and sustainable growth.

1.3. Research objective

The significances of this research are as follows:

- 1- Firstly to identify the gaps in literature by providing a comprehensive literature review on biofuel supply chain uncertainties, hedging and sustainability
- 2- Secondly, model a biofuel supply chain considering uncertainties in the decision making and using stochastic algorithm to solve the resulting problem
- 3- Thirdly to propose a hedging strategies to mitigate the risks/uncertainties within a hybrid generation biofuel supply chain (HGBSC)
- 4- Finally, to incorporate sustainability concepts in a model to provide insights as at how such decisions impact the entire supply chain

1.4. Research significance and contribution

The research conducted has its significance and contribution to the biofuel supply chain as follows:

- Designing an efficient and effective biofuel supply chain that incorporate uncertainties and uses stochastic optimization
- Contribute to the knowledge base of biofuel supply chain with uncertainties and providing suitable hedging tools against these uncertainties
- Develop sustainability models that consider economic, environmental, and social aspects of sustainability
- Providing and reviewing a comprehensive literature that for biofuel supply chain uncertainties, hedging and sustainability

CHAPTER 2: LITERATURE REVIEW: UNCERTAINTIES AND SUSTAINABILITY CONCEPTS IN BIOFUEL SUPPLY CHAIN MANAGEMENT

2.1. Abstract

Biofuel energy as an alternative and additive form of energy to fossil fuel has gained much attention in recent times. In order to sustain such a vision, a robust supply chain is of extreme importance in helping to deliver competitive biofuel to the end user markets. In this section of the dissertation, firstly, an introduction of the evolution of biofuels and the general structure of the biofuel supply chain are presented. Secondly, the three types of decision making levels and uncertainties that are inherent within the biofuel supply chain are discussed. Thirdly, important methodologies for modeling uncertainties in the decision making process are provided. Fourthly, sustainability concepts and models that give perspectives to the social, economic and environmental concepts are reviewed. Finally, conclusions and future research based on incorporating uncertainties and sustainability concepts within the biofuel supply chain are drawn and suggested, respectively.

2.2. Introduction

In order to ensure future energy security and sustainability, renewable energy has attracted the attention of researchers in both academia and industry. Biofuel energy is one of the renewable energy that has gained grounds in this regard. The U.S. Environmental Protection Agency (EPA) announced starting ethanol production at 4 billion gallons in 2006, and increasing each year by 700 million gallons. This will reach a level of 7.5 billion gallons in 2012 (EPA, 2009). These contributions are important in helping to improve the environment by reducing the

Green House Gas emission (GHG), and possibly increasing economic activities in most parts of the country (Zolin, 2008).

Biofuels include a wide range of fuels which are derived from biomass. The major products cover liquid biofuels and various biogases (Demirbas, 2009). Bioethanol is an example of liquid fuels that are used as substitutes as well as additives for transportation fuel. Biogas is methane produced by the process of anaerobic digestion of organic material by anaerobes. It can be produced either from biodegradable waste materials or by the use of energy crops fed into anaerobic digesters to supplement gas yields. The solid byproduct, digestate, can be used as a biofuel or a fertilizer.

Biofuel supply chain consists of a network of producers of the raw material (biomass), biorefineries, storage facilities, blending stations and end users. Many researchers have focused on technologies that transform biomass to biofuel. But in order to deliver a competitive end product to the end user markets, a robust, reliable and sustainable biofuel supply chain is essential (Redman, 2008). The biofuel supply chain provides three main levels of management decisions to ensure the delivery of the finished products from the origin to the destination in an efficient and effective manner. These decisions can be strategic, tactical and operational. Due to the nature of the biofuel supply chain, many uncertainties exist. The uncertainties include, but are not limited to: raw material supply and price uncertainties, finished goods demand and price uncertainties; pre-treatment uncertainties, production and yield uncertainties and transportation uncertainties. However, few literature which model uncertainties have been found. In order to achieve optimal performance, the decisions of biofuel supply chain management should incorporate these uncertainties (Redman, 2008). Therefore, this literature review discusses the

biofuel supply chain and provides some modeling methodologies. In addition, sustainability models and their impact on the present and future supply chain basis; economic, social and environmental factors are discussed.

The rest of the sections are organized as follows: Sections 2.3 and 2.4 provide an overview of the biofuel supply chain and structure. Section 2.5 considers the decision making in biofuel supply chain. Sections 2.6 and 2.7 discuss uncertainties and modeling uncertainties in the biofuel supply chain management. Sections 2.8 and 2.9 outline sustainability concepts and provide some sustainability models that can be integrated into the biofuel supply chain. Section 2.10 finally draws the conclusion and provides future research direction.

2.3. Background and evolution of biofuel

Biofuels have been in existence for decades. It can be traced to the late 1800's when their major purpose was for cooking, heating and other needs. Due to the changing technology and production for commercialization, a structured market is available for its trading (UNEP, 2009). Biofuels are being used for basic energy needs and as blends or substitutes for the traditional fuel sources, that is, petroleum.

There are currently four generations of biofuel. The raw materials of the first generation biofuels are obtained from food crops. Examples are corn, sugar beets, sugarcane, and any sugar or starch. The technological method used to produce first generation biofuel is called enzymation, or enzyme digestion that releases sugars from starchy materials in the feedstock. According to IEA (2009) the first generation biofuel are produced primarily from food crops. The raw materials used usually have higher octane rating, which measure the tendency of the fuel to burn in a particular manner that is suitable for the engine. This has gotten to the stage

where increasing measures are being made to address these limitations, by the introduction of the second and third generation biofuels.

Second and third generation biofuels are produced from residues of crop and forest, industrial wastes and non-food energy crops. The raw materials for the second generation include cellulosic materials, switchgrass, waste biomass, wheat stalks, corn stalks, wood, and special energy or biomass crops, e.g. Miscanthus. Second generation biofuels use liquid technology to transform solid biomass to biofuel (Oliver and King, 2009). This technology mimics the biological digestion of ruminants as they digest the grass they have eaten, which is called enzymatic digestion. Example of the third generation biofuel is algae, which is mostly being developed today. No commercialization production has begun yet since researchers are conducting experiments in identifying mechanisms of the decomposition of the cellulose into sugars.

One of the advantages of the second and third generation of biofuels is provision of additive impacts with the usage of raw materials that do not compete with food. This is the main reason why the second and third generation biofuels are preferred since they use raw materials that are readily available, cheap, no competition with food, and reduction in Green House Gas emissions (GHG). This is made clear by Naik, Vaibhav, Prasant, and Ajay (2009) indicating that the first-generation biofuels appeared unsustainable because of the potential stress that their production places on food commodities.

A summary of the second and third generation biofuels that they do not compete for food commodities with other types of biofuel raw materials such as corn is provided. Also, the high level of content of lignin and cellulose makes it desirable for higher carbon content which makes

it more effective and suitable for usage in bioenergy production. The benefit obviously is having less biomass being used to achieve a desired level of biofuel quantity.

The talk about fourth generation biofuels is currently ongoing and has not generated as much attention as there are still pressing policy and other needs for the first, second and third generations. Numerous organizations and startup are advancing the concept of bio-chemical and thermo-chemical processes that produce drop in fuels like green gasoline, green diesel, and green aviation fuel. This has been the case because there is no formal definition for the term fourth-generation biofuels. While some quarters have referred to it as the biofuels created from processes other than first generation ethanol and biodiesel, second generation cellulosic ethanol, and third generation algae biofuels (Chakraborty, 2008). Some fourth generation technology pathways include: pyrolysis, gasification, upgrading, solar-to-fuel, and genetic manipulation of organisms to secrete hydrocarbons. This will be limited in this discussion, but some outline of the advantages and disadvantages will be presented. Tables 1, 2 and 3 summarize the similarities, differences, and sustainability concepts of generations biofuel.

Table 1. Similarities in biofuel generation

	First generation	Second and third generation	Fourth generation
Energy security	Ensures	Ensures	Ensures
Agricultural and industrial support	Ensures	Ensures	Ensures and other extensions
Reduction of oil imports	Ensures	Ensures	Ensures
Demand and expectation	Ensures	Ensures	Not exactly known- ongoing research
Greenhouse gas emission reduction	Ensures	Ensures	Potential exists

Table 2. Biofuel generation

	First Generation	Second and third generation	Fourth generation
Type of biomass	Uses sugarcane, oil feed, corn and other food substitute as raw material	Uses switchgrass, wood waste and other cellulosic raw material	Uses combination or special process of first and second
Market for trading	Structured markets for trading	Not structured for markets for trading	Not structured for markets for trading
Production technology	Relatively mature section for production	Relatively new and not matured and good for cost reduction	Relatively new and not matured and good for cost reduction
Conversion rate	Lower conversion rate of conversion	Relatively cheaper and sometimes at no cost	Cost could be higher as heating processes are involved
Feedstock Availability	Readily available in large quantities in some places, e.g. corn in the USA	Extensive benefits on greenhouse gas emission is limited	Benefits on greenhouse gas emission but not quantified
Cost of building plant and process	This is an expensive option for energy development	Not in commercial quantity, research is still ongoing	Not in commercial quantity, research is still ongoing

Table 3. Biofuel sustainability

	First Generation	Second and third generation	Fourth generation
Environmental benefits	Provided initially breakthrough and increase octane number in gasoline	Close to meeting the claimed environmental benefits	Ongoing
Biodiversity	Might potentially have a negative impact on biodiversity	Lower conversion rate	Not relatively known
Food versus energy competition	Contribute to higher food prices due to competition with food	Lack of technological and research breakthrough	Technological and research still ongoing
Social and environmental impact	Claimed environmental and social benefits	Same	Initial thought, not proven

2.4. General structure of the biofuel supply chain

Figure 1 shows the general framework of the biofuel supply chain. The major elements in the biorefinery supply chain are; (1) farm, (2) biorefinery plants and (3) transportation. Biomass raw materials are transported by trucks from the neighboring farms to the biofuel refinery plant through the farm cooperatives. Cooperatives act as the liaison between the producers and the buyers. Storage facilities are needed between farms and biorefineries. Pretreatment storage is also provided to ensure raw material freshness and increase the conversion rate. In most cases, the feedstock or raw materials are transported from farms directly to the biorefinery. Biomass raw materials are converted into finished goods such as bioethanol, corn oil and distiller's dry grains (DDGS) at the biorefinery. The finished product is transported via trucks to terminals for blending. Blending the ethanol with gasoline is carried out so that the ethanol product will be used for fuel purposes only. This is usually done at the initial stage by denaturing it with other chemicals. The blending of ethanol and gasoline ensures the provision of various grades of

ethanol and gasoline combinations such as E85 and E15. The E85 consists of 85% ethanol and 15% of gasoline, while the E15 consists 15% of ethanol and 85% of gasoline. The blended ethanol is subsequently sent to the gasoline retail outlets, where they are sold together with other types of fuel. In the second and third generation of biofuels, terminals for fuel blending have not been given much attention. Some biofuel supply chains have a direct pre-treatment at the refinery or biofuel plants where the raw materials are sent directly as explained previously. A biorefinery plant usually uses various conversion processes to convert the raw materials into the various end products depending on if it is from any type of the generations.

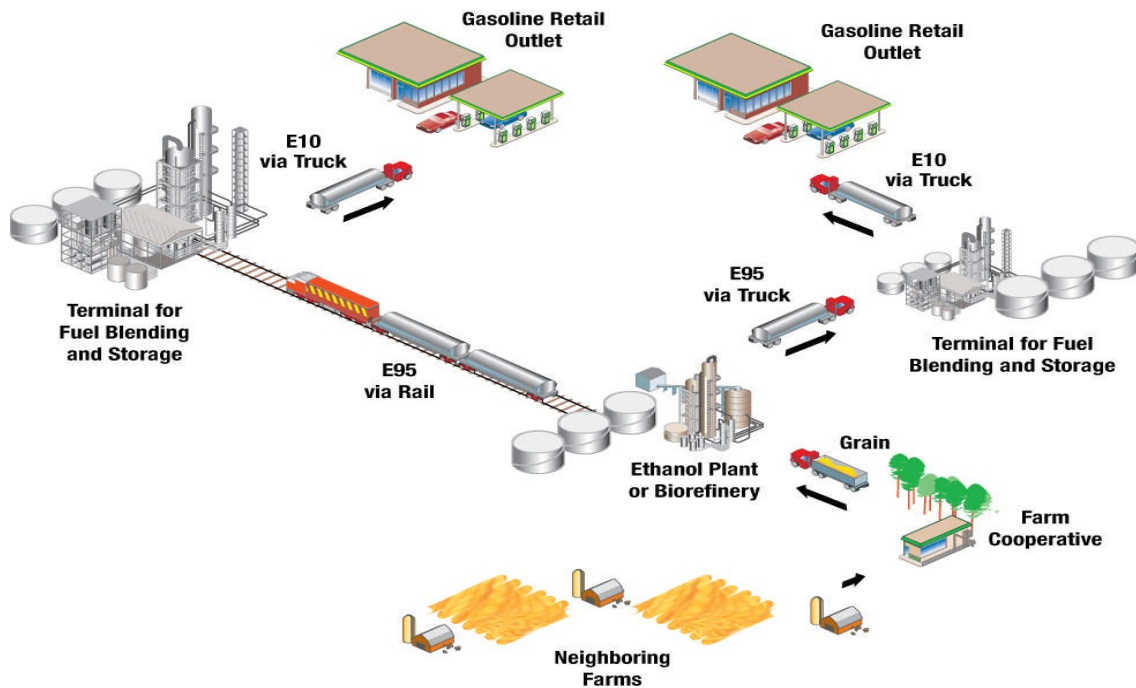


Figure 1. General framework of the biofuel supply chain

Source: National Bioenergy Center, National Renewable Energy Laboratory (2005)

2.5. Decision making in biofuel supply chain

The supply chain consists of a summarized network of suppliers, manufacturers, and end users. Supply chain management is the management of all the activities in the supply chain to ensure the efficiency and effectiveness of the material flow, information flow and cash flow. The goal of the supply chain is to ensure the delivery of quality goods and services to the customers at the right time and place. There are three main decision making processes in most supply chain management: strategic, tactical and operational decisions. Strategic decisions are long term decisions which may need revisions after five or more years depending on the business entity.

The tactical decisions are medium term decisions usually spanning between six months and one year, that take into account logistical needs, distribution parties or network and inventory planning levels. Usually this tactical decision is made to provide cost benefit due to the constraints of the strategic decisions. Finally, the operational decisions are short term decisions that are made weekly or daily and are designed to help achieve the tactical decisions outlined. An example is the detailed production scheduling, demand planning and detailed scheduling (Chopra and Meindl, 2003). The design and management of efficient supply chains in today's competitive environment should focus on optimizing all the decisions to achieve robust and reliable supply chain. Therefore, designing the supply chain of biofuel should focus on optimizing strategic, tactical and operational decisions to reduce system wide total cost or maximize profit.

2.5.1. Strategic decisions in biofuel supply chain

Strategic decisions in biofuel supply chain include, but are not limited to; (1) selection of energy production technologies, (2) network configuration, (3) supply and demand contracts, and (4) ensuring sustainability (Iakovou, Karagiannidis, Vlachos, Toka, and Malamakis, 2010).

Energy production technologies should be selected at the beginning of planning the production of biofuel. The technologies will not be changed in a short-term period. Energy production technologies include; (1) the conversion of waste biomass and organic substrates into energy, which involves a wide range of different types and sources of biomass, (2) conversion options, end user applications and (3) infrastructure requirements (Eksioglu, Acharya, Leightly, and Arora, 2009). Reasons such as raw material availability, raw material type, cost of building and maintaining the plants, energy and food debate as well as environmental and sustainability issues are all important factors to consider when choosing the type of technology to be used for the biofuel production. This is the reason the technologies cannot be changed very often (Gronalt and Rauch, 2007).

Optimal biofuel supply chain network will ensure that the biofuel can be delivered efficiently and effectively to the end-user market (Hamelinck, Suurs, and Faaij, 2005). Supply chain network design involves decisions such as sourcing and location of production facilities. One of the most inclusive studies of the design of logistics network is the strategic decision problems that need to be optimized for the long-term efficient operation of a biofuel supply chain (Atchison and Hettenhaus, 2004). The configuration of Waste to Biomass Supply Chain (WBSC) networks as studied by Huang, Chen, and Fan (2010), is comprised of critical decisions that affect the biomass flow and the associated costs. The authors refer to sourcing, procurement of biomass, purchasing, allocation and capacity of intermediate warehouses and location of energy conversion facilities as part of the strategic decisions that are taken. Some key parameters such as the capacity limit of supply nodes and the potential fixed capacity of an existing power plant by Gnansounou (2010) are also considered.

Supply and demand contracts involve decisions such as agreed terms of delivery and payment between the producer and the supplier. This might involve standard regulations as practiced in most industries (Kang, Onal, Ouyang, Scheffran, and Tursun, 2010). Some of these measures include governmental R&D programs, tax cuts and exemptions, investment subsidies, feed-in tariffs for renewable electricity and mandatory blending for biofuels quotas. Supply and demand contracts measure the intensity and fusion of having some level of conviction to lure investors. Nonetheless, sufficient biomass supply under stable and reliable conditions help in the sustainability and measure targets for stability. In providing renewable energy policies to a changing market demand for bioenergy, Leduc, Dotzauer, and Obersteiner (2008) suggested a collaborative effort from agricultural, governmental and consumer organizations to fully utilize the varied expertise that each team brings in the overall objective.

Ensuring sustainability are the types of decisions that are made to ensure the entire supply chain is sustainable, being able to support and accomplish its main functions and objective. Sustainability on the other hand ensures that the social, economic and environmental impacts of this supply chain are adequately addressed. A more detailed analysis of this will be considered in section six of this dissertation.

2.5.2. Tactical decisions in biofuel supply chain

Tactical decisions are medium term decisions that involve sourcing decisions, production decisions, scheduling, transportation and logistical contracts, and planning process definition (Iakovou, Karagiannidis, Vlachos, Toka and Malamakis, 2010). Inventory decisions such as location, quality and quantity of inventory are also considered. Decisions taken at the tactical decision level are planned towards achieving and executing the strategic decisions.

Biomass sourcing decisions are crucial in the Biofuel Supply Chain (BSC) in order to minimize the geographical distance and increase accessibility to the raw material sources among other factors. This ensures that the rather isolated geographical allotment of significant biomass is able to raise the interest of researchers into identifying the available biomass quantities over a region, and subsequently proceeding with the selection of the optimal biomass sources (Iakovou et al., 2010).

Production scheduling and inventory decisions in biofuel supply chain are types of the medium term decisions. These decisions are considered as the base of the tactical level in order to streamline the stock of finished products that are produced. Also, the amount of finish goods to be stored based on the raw material availability and overall strategy of the immediate production plan. A presentation of a novel multi-time-stage input–output-based modeling framework for simulating the dynamics of bioenergy supply chains is considered by Grisso, Cundiff, and Ravula (2008). One of the key assumptions used in the model is that the production level at the next time-stage of each segment of the energy supply chain. This adjusts to the output surplus or deficit relative to the targets at the current time period. The objective of the process was to minimize the overall cost of the supply chain by reducing the inventory level and freeing locked up working capital in the warehouse.

Transportation involves the movements of people and goods from one location to the other. Logistics on the other hand considers the management of the flow of the goods, information and other resources in order to meet customer requirements (Kumar, Sokhansan, and Turhollow, 2006). Transportation and logistics selection or contracting is another important decision in the tactical decision level which seeks to create the link between the various points of processing and delivery. Gabbar (2009) considered the capability of harvesting, storing and

transporting biomass efficiently, at a low cost. This was done by considering the transportation system of a cotton supply chain network and intermodal transportation impact. Assumption basis scheduling and pick up time on the biofuel supply chain respectively are applied. Transportation and logistics usually have a high impact on the efficiency and responsiveness of the entire chain.

2.5.3. Operational decisions in biofuel supply chain

Operational decisions are short term decisions that ensure the continuous operation of the plants and other processes in the supply chain. These decisions are made daily or weekly and sometimes several times to make sure that products are manufactured, moved and sold in a timely and cost effective manner. Some of the operational level decisions are detailed production scheduling, daily fleet management, and daily or weekly inventory review. The focus here is geared towards achieving the plan or framework set by the tactical supply chain decisions. In the biofuel supply chain, this involves daily activities and planning such as transportation and logistics scheduling, demand forecasting and review to meet the monthly targets. The manufacturing planning for the plants and the detailed production and material requirements planning are usually reviewed at this decision level (Hemelinch and Faaij, 2005).

Daily production scheduling is used by Voivontas, Assimacopoulos, and Koukios (2001) in optimizing the production of agricultural residues. The authors consider production scheduling as the operational decision, and the raw materials needed and capacity of power plants as some of the parameters in the model. A comparison is provided to investigate the energy production and the agricultural interest in satisfying the objective by Skoulou and Zabaniotou (2007).

Logistics and fleet management involve important decisions that are made within the operational decision level in the BSC. This ensures that adequate provisions are made in the delivery of the products in a timely fashion. In doing this, one of the important factors to

consider is the provision of the necessary technical tools to implement the decisions that are chosen. Papadopoulos and Katsigiannis (2002) examined logistical measurements by surveying geographical areas by using decision support system (DSS) tools. These decision support system tools help to optimize the land area for the usage of the biomass raw material (Gan, 2007). Operational decisions in the biofuel supply chain impact the material flow, timeliness, efficiency and effectiveness to ensure minimized cost of delivery (Elms and El-Halwagi, 2010).

2.6. Uncertainties in biofuel supply chain

The following paragraph discusses the major uncertainties in the biofuel supply chain. The uncertainties include, but not limited to; (1) supply, (2) transportation and logistics, (3) production and operation, (4) demand and price and (5) other uncertainties.

2.6.1. Biomass supply uncertainties

Supply uncertainties include raw material yield, type and quality (Helms and El-Halwagi, 2009). This raises major concerns in procurement decisions as indicated by Cadre and Orset (2010), Dal-Mas, Giarola, Zamboni, and Bezzo (2010), Markandya and Pemberton (2010), Meyer (2007), and Treleven and Schweikhart (1988). Most supply uncertainties in the biofuel supply chain are due to quantity of the biomass yields harvested, quality of the biomass, transportation lead time, and congestion at biomass source (Yano and Lee, 1995). Supply uncertainties can be operational and/or financial. Some of the operational and financial hedging methods are safety stock, multiple suppliers, and forward and future purchase of raw materials respectively. Table 4 outlines some of the supply uncertainties in the biofuel supply chain.

Table 4. Supply uncertainties

Paper	Uncertainty	Reasons
Caeser, Riese, and Seitz (2007)	Supply (quantity)	Shortage of feedstock, technology for harvesting and regulation influx
Nagel (2000)	Supply (quantity)	Maintaining stable supply of biomass, environmental and economic viability of alternative fuel
Ravindranath et al. (2009)	Supply (unavailability of arable land)	Land utilization for other food purposes, paper suggestion eliminating Green House Gas (GHG) emissions if biofuel is used
Berndes, Hoogwijk, and van den broek (2003)	Supply (unavailability of lands)	Unreliable supply sources possibly due to the market establishment for corn trading and not for some biomass raw material
Dautzenberg and Hanf (2008)	Supply (quantity and quality)	Supply issues due to profit participation rights rather than spot market interactions regarding the supply of raw materials

2.6.2. Transportation and logistics uncertainties

Transportation and logistics, uncertainties are the inability to deliver both biomass raw materials and finished products in a timely and cost effective manner. Examples of transportation and logistics uncertainties are delays in fleet scheduling, demand and inventory, transportation cost, lack of coordination, delivery constraints, lack of optimized containers due to low yield supply, cost of warehouse and transportation lanes availability. The provision of an effective movement and delivery of fresh products and services is one of the reasons to consider transportation and logistics uncertainties. Some of the impacts of these types of uncertainties on the supply chain are: increase in freight cost, volatile supply of raw materials and increase in inventory and warehouse cost. Table 5 outlines the uncertainties in transportation and logistics.

Table 5. Uncertainties in transportation and logistics

Paper	Uncertainty	Reasons
Schmidt, Leduc, Dotzauer, Kindermann, and Schmid (2009)	Transportation (delivery)	Unable to locate biofuel plants at an optimized location to ensure electricity and heat usage delivery
Eksioglu et al. (2009)	Transportation (intermodal)	To deliver biofuel at the least cost within the supply chain

2.6.3. Production and operation uncertainties

Production and operation uncertainties cause the inability to produce the planned quantity of production. Some of these uncertainties are delays in raw materials acquisition, production yields, machine breakdown, lead time constraints and inventory decisions. One of the importance of production and operation uncertainties is to reduce excess inventories that may lock up working capital. This results in having limited inventory which might cause losses in profit. Some impacts of production and operation uncertainties are excessive interruption in production and increase machine idle time. Table 6 summarizes some of the uncertainties in the production of biofuel supply chain.

Table 6. Showing the production and operation uncertainties

Paper	Uncertainty	Reasons
Cruz, Tan, and Culaba (2009)	Production (supply of raw material)	To be able to stabilize demand variation and therefore simulating raw material delivery to the plant
Ochoa, Wozna, and Repke (2010)	Production (inventory balance)	Unable to create an inventory and delivery balance and therefore adopting a plant wide control process

2.6.4. Demand and price uncertainties

Demand uncertainty refers to the unknown or unpredictable variations in the quantity and timing of demand as experienced in a supply chain. Price uncertainty defines the chance or

speculation that price of a product might change. Demand and price uncertainties, include, but not limited to, raw material cost (e.g. corn prices), crude oil price, tax subsidies, carbon trading, and governmental policies. Incorporating demand and price uncertainties into the decision making process can reduce expectation for profit generation. Table 7 outlines some of the uncertainties due to demand and price with reasons.

Table 7. Demand and price uncertainties

Paper	Uncertainty	Reasons
Meyer (2007)	Demand & price (market volatility)	Evaluating the impact of food security through high energy demand
Markandya and Pemberton (2010)	Demand & price (market volatility)	Unable to fully assess the impact of tax on energy markets due to volatility
Ravindranath et al. (2009)	Price (biomass raw material)	To develop a model pattern for the spatially explicit supply chain
Cadre and Orset (2010)	Price (market size)	To be able to invest in the biofuel supply chain considering the market structure

2.6.5. Other uncertainties

Other types of uncertainties in the biofuel supply chain are sustainability, tax, governmental policies, and regulatory policies. Sustainability uncertainties are meant to bridge the gap between the economic aspects of biofuel, and the social implications. The utilization of the resource without any social and environmental policies is detrimental to the sustainability concept. Table 8 summarizes the uncertainties due to other forms.

Table 8. Other uncertainties in the biofuel supply chain

Paper	Uncertainty	Reasons
Hammond, Kallu, and McManus (2007)	Other (carbon emission)	Unable to evaluate the actual carbon emission to indicate number in the market
Mortimer and Elsayed (2006)	Other (carbon, methane, nitrogen emission)	To fully determine the amount of methane and other nitrous gas effects on the environment
Rozakis and Sourie (2005)	Other (tax exemptions)	To develop a model estimates the cost and surplus by employing tax exemptions

2.7. Modeling uncertainties in biofuel supply chain

Due to the nature of the biofuel supply chain, uncertainties exist in all the echelons of the supply chain. In order to eliminate the impact of these uncertainties, we need to incorporate them into the decision making process. The following sections discuss the popular methodologies used to incorporate uncertainties in supply chain management.

2.7.1. Analytical methods

Analytical methods are one of the methodologies that are used to solve problems with uncertainty. Some of these methodologies are Stochastic Mixed Integer Linear Programs (SMILP), Integer Stochastic Programming (ISP), Stochastic Mixed Integer Non-linear Programs (SMINLP), Markov Decision Process (MDP) and Linear Programs (LP) with Scenario Generation (SG). These methods have seen applications in other supply chains, and might yield significant results if applied in the biofuel supply chain.

The work of Dal-Mas et al. (2010) developed an improved stochastic method based on the Stochastic Mixed Integer Linear Programming (SMILP) method. It uses an improved solution method, based on the sample average approximation technique. This technique is integrated with the accelerated Benders decomposition for the improvement of the mixed integer

linear programming solution phase. This solution method is applicable to problems with large number of scenarios.

In Kim and Realf (2011), the application of an Integer Stochastic Programming (ISP) method based on a two-stage stochastic capacity planning model is used. Benders decomposition method is applied to solve this problem. The models give some computational results based on serial and parallel implementations of the algorithms that are used. First, an analysis of the wait and see models is presented and then, the results of this analysis are incorporated into the stochastic representation of the model.

Sodhi and Tang (2009) introduced a two-stage stochastic model for supply chain management under uncertainty by applying a Stochastic Mixed Integer Non-linear Method (SMINLP). The decisions are to determine the production topology, plant sizing, product selection, product allocation and vendor selection. The proposed solution algorithms are based on branch and fix algorithm. The branch-and-fix approach is introduced for coordinating the selection of the branching nodes, and the scenario subproblems to be jointly optimized.

A multi-period stochastic planning model using finite scenario generation is developed by Lababidi, El-Wakeel, Alatiqi, Al-Enzi (2003). The technique applied is generating scenarios for the mean with given standard deviations as the stochastic terms. The proposed supply chain consists of decisions such as amount of crude oil to purchase, how much to produce, and other processing and distribution requirement. The solution utilized was known to be effective as compared to the other methods such as Expected Value of Perfect Information (EVPI).

Othmani, Lababidi, Alatiqi, and Al-Enzi (2008) proposed an auxiliary Markov Chain model for uncertainty in lead time. The solution technique based on using the time Auxiliary Markov Chain was found not to be effective, and a method of using the general optimization

algorithm is proposed. The paper focused on the search of the optimal values of the planned lead times for the Material Requirement Planning (MRP) method for the supply chain planning.

2.7.2. Simulation methods

Simulation methods are important tools for solving supply chain problems with uncertainties. There are different kinds of simulation: static, dynamic, discrete and continuous, deterministic and stochastic. This depends on the system state and case. In this work, Monte Carlo (MC) and Discrete Event (DE) simulations are presented. Generally, the MC simulation is used to solve static problems, an example is the Scenario Generation (SG). The DE simulation can be used for solving dynamic systems, such as queuing systems. For further reading on Monte Carlo, Scenario Generation and Queuing Systems, refer to [c- f].

2.7.2.1. Discrete event simulation methods

Discrete Event simulation methods can be applied to many supply chain problems to solve uncertainties.

Jun, Blau, Pekny, Reklaitis, and Eversdyk (2004) used a simulation based optimization approach to solve a deterministic planning and scheduling model, which incorporate safety stock levels as a means of accommodating demand uncertainty. The simulation based optimization framework is developed for decision making with respect to project portfolio selection and project task scheduling. The computational framework, called the “Sim-Opt”, combines deterministic mathematical programming for maximization of net present value.

A simulation methodology developed by Kerbache and Smith (2004) is based on analytical queuing networks, with nonlinear optimization, to design supply chain topologies and evaluate performance measures. The simulation approach is based on different network scenarios

for the uncertain parameters. The results obtained from the network configurations demonstrated this technique as a useful tool to analyze congestion problems, and to evaluate the performance of the network topologies.

The paper by Higuchia and Trout (2004) uses a queuing network dynamic simulation to study the short product life cycle case shown by Tamagotchi. To simulate the supply chain dynamics, all the echelons are consisted of scenarios based on the Tamagotchi case, and are integrated into the dynamic model. The model has three components; market, retail and factory for the uncertainty analysis.

2.7.2.2. Monte Carlo simulation methods

Many supply chain stochastic problems have applied Monte Carlo simulation to solve uncertainties. A stochastic simulation based on dynamic system is used in modeling a network design consisting of plants, warehouse and possible customer based locations by Hung, Kucherenko, Samsatli and Shah (2004). A solution technique based on the Monte Carlo simulation and sampling techniques is used. A Markov Decision Process (MDP) based on Monte Carlo Sampling technique in providing a cost effective supply chain management is considered by Subrahmanyam, Peknyt, and Reklaitis (1994). The solution technique employed an algorithm that uses a decomposition approach for the scalability of the problem.

To solve a bi-criteria model, a hybridization of multi-objective particle swarm optimization and simulation optimization are considered by Jung, Blau, Peknyt, Reklaitis, and Eversdy (2004) and Mahnam, Reza, Vahid, Seyed, and Hejazi (2009) respectively. The papers employed the Monte Carlo based approach for the mean and standard deviation of the uncertain parameters in each case. The solution found was known to be effective and insightful in solving

a supply chain problem with demand uncertainties. Miranda and Garrido (2004) applied a scenario generation technique through a simulation approach applied based on discrete event simulation. The uncertainty is to make a decision for production based on fuzzy demand and unreliable supply. A solution technique based on solving the LP after simulation is used.

2.8. Sustainability concepts and models in biofuel supply chain

Sustainability means meeting today's energy needs for environmental stewardship, economic prosperity, and quality of life without compromising future generations' ability to meet these needs of energy for themselves (Sabri and Beamon, 2000). As discussed by Altiok and Ranjan (1995), Ayuso and Escudero (2003), Levis and Papageorgiou (2004), assessing the true potential of sustainability will require the production, trade and final conversion of the biofuel. Sustainability concepts must be analyzed taking into consideration the issues of the environment and socio-economic policies (Amigun, Musango and Stafford, 2011; Duku, Gu, and Hagan, 2010; Renewable Fuel Standards, 2011; Treleven and Scweikhart, 1998).

2.8.1. Environmental concept

Environmental sustainability outlines policy visions that have been laid down to prevent the degradation of the agricultural forest, and decrease the GHG emission and other environmental issues (Tan, Aviso, Barilea, Culaba, and Cruz, 2011). The major issues of environmental sustainability are; (1) GHG emission, (2) water resources quality (3) soil degradation and loss of biodiversity.

Greenhouse gas is the atmospheric gas that absorbs and emits radiation. In biofuels, the amount of emission is lower as compared to gasoline. Biofuels burn cleaner than gasoline, resulting in fewer greenhouse gas emissions. Biofuels are fully biodegradable, in comparison with other fuel additives. Cellulosic ethanol has the potential to cut greenhouse gas emissions by

up to 86% (U.S. Department of Energy, 2011). Ethanol is a safe, high-performance replacement for most fuel additives. The use of ethanol can increase emissions of some air pollutants, because fossil energy is used during the farming of biomass crops and during biofuel production. These emissions can be reduced by using renewable power and improved farming methods.

Clean, fresh water is essential to public health and environment. The impact of biofuels on water quality is due to the issue of intensified and expanded corn production on water quality. The increase in demand for energy crops will result in price rise in crops encouraging farmers to grow more feedstock based crops. Corn, soy, wheat and other profitable crops will be grown to increase crop yields. High corn prices will encourage farmers to expand total acreage of land under cultivation, therefore affecting lands set aside for erosion control and habitat protection (Wood Institute for the Environment, 2006).

Soil degradation and erosion is the washing away of the surface of land as a result of rain, wind and other man-made and natural phenomenon. In the absence of strict enforcement of best practices, these issues can increase. An analysis on ensuring yield gains is not achieved at the expense of environmental quality. Each of these actions might increase erosion and contaminated runoff into streams, rivers and oceans leading to soil erosion. A further increase in erosion could occur if high corn prices reduce the attractiveness of financial incentives offered to farmers. This will prevent putting erosion prevention plans in place as part of USDA's Conservation Security Program (Wood Institute for the Environment, 2006).

2.8.2. Economical concept

The economic issue of biofuel includes, but not limited to the following; (1) food versus fuel debate, (2) efficiency and energy balance, and (3) increasing biofuel budget programs

(Amigun et al, 2011; Inderwildi and King, 2009; Karagiannidis, Wittmaier, Langer, Bilitewski, and Malamakis, 2009).

Food versus fuel debate is attributed to many biofuel feedstocks like corn, sugarcane, and soybeans that are key sources of food being substituted for energy. Production of crops for bioenergy uses may displace food-related crops. This can increase the cost and decrease the availability of foodstuffs, including plant and animal-based foods (Duku and Hagan, 2010). This is the reason second, third and fourth generation biofuels feed stocks such as cellulosic grass, switchgrass, miscanthus and algae are being explored currently. These raw materials do not compete with food, and provide higher conversion rates, and cheap cost of cultivating.

Efficiency and energy balance is the goal to expend less energy by using energy efficient materials and means. Energy related raw materials and means are configured and changed to become more energy efficient, meaning they use less energy to make their product. Energy efficiency and renewable energy interrelationship is the twin pillars of sustainable energy policy (Green Collar Operations, 2010). Greenhouse gases have also been connected with products that are less energy efficient.

Increasing biofuel budget programs can increase the economic activities of farmers. This is achieved in the area of feedstock cultivation, new land acquisition, varying land for different commodity harvesting, and increase revenue from investors (Demirbas, 2009). Research expansion to include variety of feedstock for cellulosic technology will enable processors to take advantage of the flow of a variety of biomass feedstock. This will encourage water-friendly feedstock of perennial grasses and trees.

2.8.3. Social concept

This is to analyze the social issues of biofuel development, for example, the potential of technological innovation and how it enhances the society. Some of the issues of social sustainability concept include; (1) poverty reduction potential, (2) land and crop indirect impacts, and (3) effects on social resources, such as water utility systems.

The development of biofuels occurs in the rural areas where there are opportunities for agriculture. These areas are inhabited by the under privileged, and in some cases small-scale and subsistence farmers. Biofuel is argued to contribute to poverty alleviation through provision of energy by increasing the income and economic per capita (Bell, Silalertruksa, Gheewala, and Kamens, 2011). Distribution of this wealth can create equity and improvement in the quality of life of communities that have biofuel developments. States like North Dakota can commit to promote biofuels mainly in response to societal development and poverty alleviation agenda. The achievement of this goal can be developed through a structured development program.

Land is central to the issue of biofuel production. In order to gain maximum benefit from biofuels, large tracks of land are required for biofuel crop production. Land and crop indirectly affect the land tenure system and the decision on the variety of feedstock to invest in. High corn prices encourage farmers to expand the total acreage of land under cultivation. This possibly leads into lands set aside for erosion control and habitat protection. Conventional management methods in differentiating these land uses according to physical criteria (Peskest, Slater, Stevens, and Dufey, 2007). However, actual land uses, not only change according to physical factors, but change in demands from market opportunities, society and stakeholders' entitlement.

The production of liquid biofuels is rapidly increasing, mainly due to the establishment of large scale biofuel feedstock plantations. Provision of quality water, is therefore essential in this

regard (Bass, Hawthorne, and Hughes, 1998). Clean, fresh water is essential to public health; therefore a reliable water utility system is essential. In the short term, the impact of biofuels on water system quality will be inadequacy and pollution of water. This might be due total land acquisition increasing raw material cultivation.

2.9. Modeling sustainability issues in supply chain

Modeling sustainability issues is to integrate the interdependence of environmental, social, and economic concepts in the supply chain decision making. There is little literature that models the sustainability issues in biofuel supply chain. But some models have been found in general supply chain problems.

A Mixed Integer Linear Programming (MILP) model is developed by Paksoy (2010) for a multi period supply chain. The decision is to determine the optimal values of the quantities between sites and the CO₂ emission trading. The model is solved by using a direct methodology based on the simplex method.

Bertz and Gunnthorsdottir (2009) propose a model which describes the physical relationships among different environmental activities and the natural water cycle, to evaluate the economic impact of water policy sustainability. An integrated material flow account approach is evaluated. This framework allows the analyst to consider both the effect of given policies on the water cycle and the constraint produced by the sustainability problem on the economic system.

Van Dam, Klerk-Engels, Struik, and Rabbinge (2005) present a conceptual model relating plant and soil biodiversity framework for future studies in soil degradation. A discussion of the economic benefits of soil biodiversity to society as part of a wider strategy of conserving

and using agro based biodiversity. Further interrelation on how management options might be interfaced with farmers' knowledge in taking management decisions.

Zhou, Cheng, and Hua (2000) develop an economic model that examines the tradeoffs in resources and consumption due to crop-based biofuel development. A proposed solution framework based on a utility function representing consumption of a number of goods is discussed. To assist with the sector development that maximizes welfare gains, a suggestion of a number of key indicators used in constructing a typology is given. Final demonstration on the developing of renewable energy sources with maximum impact on human welfare and development.

Al-Sharra, Elkamel, and Almanssor (2010) propose a goal programming (GP) model to address efficiency and energy balance in a multi-objective supply chain sustainability. The analytic hierarchy process (AHP), a multi-objective decision making method, is used to evaluate the priorities of goals and weights of the deviation variables. The application of this approach is illustrated through a case study on sustainable supply chain optimization and scheduling of a petrochemical complex. The results obtained show that this approach is offers flexibility in the supply chain realizations for decision making with sustainability.

In applying sustainability indicators as objectives for a mixed-integer optimization model, Rentizelas, Tolis, and Tatsiopoulos (2008) developed a balanced petrochemical network to reduce entire network cost of a typical petrochemical industry. A simple Monte Carlo simulation is used to accommodate variations in prices and demand. The results indicate a useful balance in cost reduction, by incorporating rice uncertainties in price, comparing with economic effects in all three types of sustainability.

Todorov and Manirova (2009) applied correlation and descriptive analysis in the incorporation of poverty reduction as part of sustainability in a developing economy. The paper shows that reliable energy-based indicators of poverty can be created through one-dimensional indicator and the explanatory power of energy poverty indicators. A final conclusion is made basis that energy indicators are not restricted to environmental and economic issues, but is also relevant for social issues.

An inexact-stochastic quadratic programming is developed by Hutchins and Sutherland (2008) with recourse method to tackle nonlinearities of a marginal utility system. The objective is to evaluate the benefits and costs analysis for the water system uncertainties. The developed method is applied to a case study of planning resources management and developing regional ecological sustainability.

2.10. Conclusions and future research

Renewable energy is an important part of today's energy sources. Biofuel is one of the renewable energy types that serve as an alternative and additive to fossil fuel for transportation purposes. In this section of the dissertation, a provision of the general overview of the background and structure of the biofuel supply chain is considered. Also, a literature of the decision making process, and the uncertainties in the supply chain are provided. Subsequently, methodologies that have been applied in other supply chain to handle uncertainties are provided. Finally, sustainability concepts and models are discussed, and suggestions made for the incorporation of sustainability models.

Due to the uncertainties in the biofuel supply chain, it is important to incorporate these uncertainties in the decision making process. Further solution methods should be explored in considering these uncertainties. Methodologies such as analytical, simulation and other hybrid

methods can be utilized in solving biofuel supply chain problems with uncertainties. Some hedging strategies need to be considered to hedge the risks in biofuel supply chain. The risks include risks from feedstock supply and price, oil price shocks, and other forms of risks within and outside the biofuel supply chain. Applying operational and financial hedging tools will be a potential research direction.

Modeling uncertainty in the biofuel supply chain can be achieved by using either scenario or distribution based approaches. In the scenario based approach, the uncertainty can be described by a set of discrete scenarios, capturing future uncertainty. Each scenario can be associated with a probability level representing the decision maker's expectation of the occurrence of a particular scenario. The distribution based scheme can be used when a set of discrete scenarios cannot be identified, and only a continuous range of potential figures can be predicted. Incorporating these processes in modeling biofuel supply chain uncertainties might be useful in obtaining optimal decision.

Literature in modeling sustainability issues in biofuel supply chain has not been given the needed attention. However, sustainability issues impact the health of the biofuel supply chain. The effect of underestimating sustainability can lead to planning decisions that are either risky or will not take advantage of the opportunities that higher levels of sustainability provide. Therefore, models that seek to combine economic, social and environmental sustainability concepts should be a future direction of research in biofuel supply chain.

The most important reason for making biofuel an option for renewable energy is to increase energy security, sustainability, as well as to deliver competitive lower cost products to the end-user market. In order to achieve a higher level of optimization, the biofuel supply chain management should apply models that incorporate uncertainty and sustainability concepts. For

instance, to explore the optimal decisions in the production quantity of biofuel, we should incorporate demand and price uncertainties as well as sustainability issues like carbon trading.

Finally, an optimal supply chain should be designed for the new generation of biofuel in order to commercialize the products. Uncertainties and sustainability issues should be considered and incorporated when modeling the new generation biofuel supply chain management problems.

CHAPTER 3: OPTIMIZATION MODEL IN BIOFUEL SUPPLY CHAIN WITH DEMAND AND PRICE UNCERTAINTIES

3.1. Abstract

In this section of the dissertation, we propose a stochastic production planning model for a biofuel supply chain under demand and price uncertainties. The supply chain consists of biomass suppliers, biofuel refinery plants and distribution centers. A stochastic linear programming model is proposed within a single-period planning framework to maximize the expected profit. Decisions such as the amount of raw materials purchased, the amount of raw materials consumed and the amount of products produced are considered. Demands of end products are uncertain with known probability distributions. The prices of end products follow Geometric Brownian Motion (GBM). Benders decomposition (BD) with Monte Carlo simulation technique is applied to solve the proposed model. To demonstrate the effectiveness of the proposed stochastic model and the decomposition algorithm, a representative supply chain for an ethanol plant in North Dakota is considered. To investigate the results of the proposed model, a simulation framework is developed to compare the performances of deterministic model and proposed stochastic model. The results from the simulation indicate the proposed model obtain higher expected profit than the deterministic model under different uncertainty settings. Sensitivity analyses are performed to gain management insight on how profit changes due to the uncertainties affect the model developed.

3.2. Introduction and literature review

Today's energy consumption is increasing tremendously. Recent studies have shown that mainstream crude oil cannot sustain the volume of worldwide demand and consumption of

energy (Elghalia, Clifta, Sinclair, Panoutsoub, and Bauen, 2007; Lin, Ying, Chaitep, and Vittayapadung, 2008; Ou, Zhang, Chang, and Guo, 2009; Salameh, 2003). Renewable energy, specifically biofuel, has gained attention as a competitor and alternative source of energy to crude oil, especially in the transportation sector. In order to ensure a consistent and a competitive supply of these biofuels to the distribution centers, a reliable and resilient supply chain is needed to help coordinate and streamline the demand and supply activities. Literature that has considered biofuel supply chain has not extensively incorporated uncertainties into the supply chain decision-making (Awudu and Zhang, 2012; Gan, 2007; Grisso et al., 2008; Hamelinck et al., 2005; Morrow, Griffin, and Mathew, 2006). Incorporation of uncertainties in the supply chain decision-making process helps to make better decisions in realizing the overall objective of the supply chain (Hammond et al., 2007; Niknam, Khodaie, and Fallahi, 2009; Yongxi, Chien, Yuevue, 2010). However, most of the applications in the biofuel supply chain have focused on deterministic problems, such as network optimization and plant location problems by using mixed integer linear programming (MILP) methods (Eksioglu, 2009; Ravindranath et al., 2009; Schmidt, Leduc, Dotzauer, Kindermann, and Schmid, 2010; Shah, Adjiman, and Dunnett, 2008; Van Dyken, Bakken, and Skjelbred, 2010; Subrahmanyam et al., 1994; Tembo, Epplin, Hunke, 2003; Voivontas et al., 2001; Zamboni, Bezzo, and Shah, 2009). Not enough attention has been given to incorporate demand, production, price and other forms of uncertainties in the supply chain decision-making process. Decisions based on deterministic assumptions will result in non-optimal solutions if uncertainties exist. In the biofuel supply chain system, multiple uncertainties such as demands and prices of end products exist; therefore it is essential to develop an optimization model in the biofuel supply chain decision-making that considers existing uncertainties.

Uncertainties in the supply chain have attracted a lot of attention because of its importance in decision-making, and biofuel supply chain uncertainties are not an exception. These uncertainties can be incorporated at the strategic, tactical and operational decision-making levels within the supply chain. Accurately incorporating uncertainties into the biofuel supply chain will result in better decision-making and give significant improvement of the expected profit and cost. Although this is crucial within the entire supply chain decision-making process, most models that have discussed biofuel supply chain have not discussed these uncertainties extensively. This section of the dissertation combines both.

The objective of this section is to maximize the profit of a multi-product, single-period, three-echelon supply chain system subjected to uncertainties in demands and prices of end products. The problem is modeled as a stochastic programming problem, with key decisions such as products production volume, amount of raw material purchased, and the amount of raw materials consumed. To solve the stochastic problem, the decision variables are separated into first-and second-stage decisions. The first-stage decisions are the initial amount of raw materials purchased, volumes end products to be produced, and the raw material consumed. Decisions such as the amount of end products sold, backlog, and lost sales are considered as second-stage decisions. This means postponing the rest of the decisions for the next period after the realization of the uncertainty. The Benders decomposition with Monte Carlo simulation technique is used to solve the proposed model. To demonstrate the effectiveness of the proposed stochastic models and decomposition algorithm, a realistic representative biofuel supply chain in North Dakota is presented.

The rest of the sections are organized as follows: Section 3.3 gives a summary of the problem statement. Section 3.4 presents the deterministic model. In section 3.5, the proposed

stochastic models are presented. In section 3.6, the Benders decomposition with simulation algorithm is discussed. Section 3.7 provides the numerical experimental design and analyses. Final conclusions and future work are discussed in Section 3.8.

3.3. Problem statement

This section of the dissertation studies a biofuel supply chain as shown in Figure 2. The supply chain consists of three layers: biomass raw materials sources, biofuel refinery plants, and distribution centers. There are i number of raw material sources, k number of plants, and c number of distribution centers. The number of end products of biofuel refinery are represented by the term j . Representation set for the probability, and number of scenarios, are expressed as p , and ξ respectively. Biomass raw materials are transported from the sources of raw materials (via truck or rail) to the biofuel plants. Blending of ethanol and the sales of the products take place at the biofuel plants and demand locations respectively. Demands for these products are imposed by external customers. Depending on the producer's option, the products are either sold directly or traded on the Chicago Merchantile Exchange (CME).

In this section, the type of feedstock available from the raw material suppliers is corn. This input raw material is converted into corn ethanol as the main product, as well as corn oil and DDGS as the by-products. The production process used is the wet milling process (Pimentel, 2009).

Meanwhile, initial inventory at the plants for both raw materials and end products are given. Costs, such as inventory holding, backlog and lost sales are added at the producer's expense. Demands of end products are random with known probability distributions. The prices of end products follow the Geometric Brownian Motion (GBM).

The problem objective is to maximize the biorefinery plant profit by considering decisions such as: 1) the amount of raw materials purchased from each supplier, 2) the amount of products produced, 3) the amount of products sold, 4) the amount of raw materials consumed, and the 5) the end products and raw material inventory left at the first-stage. A stochastic linear programming model is proposed, and the uncertainties are incorporated in the demand and price of the finished products.

Traditionally, supply chain management problems have been modeled as deterministic problems. We will first present a deterministic model for comparison purposes, and then propose a stochastic model to realize higher expected profit. All the symbols used are defined in the notation.

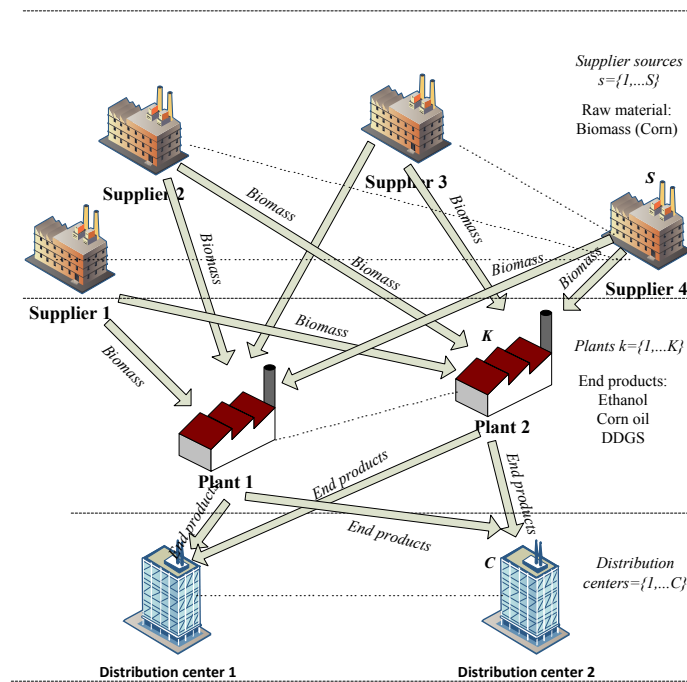


Figure 2. Biofuel supply chain process flow

Notation Index

i	represents supply sources of raw materials $i=1,2,\dots,I$
j	represents the product $j=1,2,\dots,J$
k	represents the refinery $k=1,2,\dots,K$
c	represents the customer distribution centers $c=1,2,\dots,C$

Decision Variables

$x_{i,k}$	amount of biomass raw materials from supply source i to plant k
$s_{j,k}$	amount of product j sold at plant k
$z_{j,k}$	amount of product j produced at plant k
$v_{i,k}$	amount of raw materials from supply source i consumed at plant k
$R_{i,j}$	amount of raw materials inventory from supply source i for product j
$F_{j,k}$	amount of end products j at plant k
$L_{j,k}$	amount of lost sales of product j at plant k
$B_{j,k}$	amount of backlog of product j at plant k

Parameter

$P_{j,k}$	selling price of product j at plant k
$\theta_{i,k}$	available biomass from the supply source i at plant k
$\Delta_{j,k}$	conversion factor for the end product j at plant k
$y_{i,k}$	unit cost of raw materials from supply source i at plant k
$\tau_{i,k}$	unit transportation cost of raw materials from supply source i to plant k
$\tau_{k,c}$	unit transportation cost of end products from plant k to demand point c
$d_{i,k}$	transportation distance of raw materials from supply source i to plant k
$d_{k,c}$	transportation distance of end products from plant k to demand point c
$F_{j,k}^0$	end products inventory for previous period at plant k for product j

$R_{i,k}^0$	raw material inventory for previous period at plant k for raw material from source i
$B_{j,k}^0$	amount of backlog for previous period at plant k for product j
$L_{j,k}^0$	amount of lost sale for previous period at plant k for product j
$\beta_{i,t}$	cost for processing raw material from supply source i
$m_{j,k}$	cost for lost sales for product j at plant k
$q_{j,k}$	cost for backlog for product j at plant k
$D_{j,k}$	demand for product j at plant k
$v_{i,k}$	amount of raw materials consumed from supply source i at plant k
$\gamma_{j,k}$	amount of fractional lost in demand for product j at plant k
S_0	initial spot price of the end products

Stochastic Variables and terms

ξ	scenario representation for the stochastic variable
p_ξ	probability of the scenario of each stochastic variable
$S_{j,k,\xi}$	stochastic sales amount of product j at plant k based for the scenario ξ
$B_{j,k,\xi}$	stochastic backlog for previous period at plant k for product j based on the scenario ξ
$F_{j,k,\xi}$	stochastic end products inventory in previous period at plant k for product j scenario ξ
$L_{j,k,\xi}$	stochastic lost sale for previous period at plant k for product j based on the scenario ξ
$P_{j,k,\xi}$	stochastic price of finished goods of product j at plant k for the scenario ξ
S_t	calculated spot price of the end products after the price scenarios have been generated
l	iteration steps for benders decomposition
N	total number of scenarios generated

3.4. Deterministic model

In the deterministic model, the demands and prices of the end products are constant. The mean values are used. The objective function is to maximize the producer's profit under certain constraints. Decision variables such as the amount of raw materials purchased, the amount of raw materials consumed, the end products produced, and the inventory of the raw materials, and end products are also considered. The objective function and constraints are presented below.

Objective function:

$$\begin{aligned}
Max \sum_{j=1}^I \sum_{k=1}^K P_{j,k} s_{j,k} - \sum_{i=1}^I \sum_{k=1}^K y_{i,k} x_{i,k} - \sum_{i=1}^I \sum_{k=1}^K \tau_{i,k} d_{i,k} x_{i,k} - \sum_{k=1}^K \sum_{c=1}^C \sum_{j=1}^J \tau_{k,c} d_{k,c} z_{j,k} - \sum_{i=1}^I \sum_{k=1}^K h_{i,k} R_{i,k} - \sum_{j=1}^J \sum_{k=1}^K h_{j,k} F_{j,k} \\
- \sum_{i=1}^I \sum_{k=1}^K \beta_{i,k} v_{i,k} - \sum_{j=1}^J \sum_{k=1}^K m_{j,k} L_{j,k} - \sum_{j=1}^J \sum_{k=1}^K q_{j,k} B_{j,k}
\end{aligned} \quad (3.1)$$

The objective function seeks to maximize profit, which is equal to the revenue minus the total cost. The revenue includes the total sales of biofuel and the by-products. The total cost consists of the raw materials purchasing cost, the transportation cost for both raw materials and end products, and the inventory holding costs for raw materials and end products. Other costs are the cost of loss sales and backlog ordering costs, as well as the processing cost of raw materials into end products.

s.t.

Capacity constraints:

$$x_{i,k} \leq \theta_{i,k}, \quad \forall i, \forall k \quad (3.2)$$

$$v_{i,k} \leq x_{i,k}, \quad \forall i, \forall k \quad (3.3)$$

Demand constraints:

$$B_{j,k} + D_{j,k} = s_{j,k} + L_{j,k} + B_{j,k}, \quad \forall j, \forall k \quad (3.4)$$

$$L_{j,k} = \gamma_{j,k} (D_{j,k} + B_{j,k} - s_{j,k}), \quad \forall j, \forall k \quad (3.5)$$

Raw material and finished products inventory constraints:

$$R_{i,k} = R_{i,k}^0 + x_{i,k} - v_{i,k}, \quad \forall i, \forall k \quad (3.6)$$

$$F_{j,k} = F_{j,k}^0 + z_{j,k} - s_{j,k}, \quad \forall j, \forall k \quad (3.7)$$

Material balance constraints:

$$z_{j,k} = \Delta_{j,k} \left(\sum_{i=1}^I v_{i,k} \right), \quad \forall i, \forall j, \forall k \quad (3.8)$$

Sales, demand and production balance constraints:

$$s_{j,k,\xi} \leq z_{j,k}, \quad \forall j, \forall k \quad (3.9)$$

$$s_{j,k,\xi} \leq D_{j,k,\xi}, \quad \forall j, \forall k \quad (3.10)$$

$$x_{i,k}, z_{j,k}, D_{j,k}, v_{i,k}, s_{j,k,\xi}, R_{i,k}, F_{j,k}, \theta_{i,k}, L_{j,k}, B_{j,k} \geq 0, \quad \forall i, \forall j, \forall k \quad (3.11)$$

Equation 3.2 indicates that the amount of raw materials supplied is not exceeding the amount available from the source.

Equation 3.3 is the amount of raw materials consumed not exceeding the amount of raw materials available.

Equation 3.4 and 3.5 are the demand balance constraint and the lost sales with backlog constraint.

Equation 3.6 to 3.8, are the material balance constraints for the raw materials, end products and the conversion flow for the finished goods.

Also, Equation 3.9 and 3.10 state that the amount of end products sold should be less than the amount produced and the demand respectively.

Equation 3.11 is to ensure that all the decisions variables are always non-negative.

3.5. Proposed stochastic model

Due to the existence of the uncertainties, such as uncertain prices of the end-products and demand, the deterministic model is not suitable to optimize the expected profit. Therefore, this section of the dissertation proposes a stochastic linear programming model to incorporate the uncertainties in the decision making.

Probabilities and scenarios are introduced in the objective function and constraints.

The objective function and constraints for the proposed stochastic model are provided below:

$$\begin{aligned}
 Max \quad & \sum_{j=1}^J \sum_{\xi}^N \sum_{k=1}^K p_{\xi} P_{j,k,\xi} s_{j,k,\xi} - \sum_{i=1}^I \sum_{k=1}^K y_{i,k} x_{i,k} - \sum_{i=1}^I \sum_{k=1}^K \tau_{i,k} d_{i,k} x_{i,k} - \sum_{k=1}^K \sum_{c=1}^C \tau_{k,c} d_{k,c} z_{j,k} - \sum_{i=1}^I \sum_{k=1}^K h_{i,k} R_{i,k} \\
 & - \sum_{j=1}^J \sum_{\xi}^N \sum_{k=1}^K p_{\xi} h_{j,k} F_{j,k,\xi} - \sum_{i=1}^I \sum_{k=1}^K \beta_{i,k} v_{i,k} - \sum_{j=1}^J \sum_{\xi}^N \sum_{k=1}^K p_{\xi} m_{j,k} L_{j,k,\xi} - \sum_{j=1}^J \sum_{\xi}^N \sum_{k=1}^K p_{\xi} q_{j,k} B_{j,k,\xi} \quad (3.12)
 \end{aligned}$$

The objective function Equation 3.12 is to maximize the expected profit, which can be obtained by subtracting expected total cost from expected revenue. Due to the uncertain demands and prices of the end products, the first part of the Equation 3.12 is used to calculate the expected revenue by considering the probability of each scenario. The rest parts of the Equation 3.12

determine the total cost. The total cost comprises of the raw materials purchase cost , raw material transportation cost, the production cost of end products, the expected inventory holding cost of raw material and end products, expected lost sales and expected backlog cost.

s.t.

Capacity constraints:

$$x_{i,k} \leq \theta_{i,k}, \quad \forall i, \forall k \quad (3.13)$$

$$v_{i,k} \leq x_{i,k}, \quad \forall i, \forall t \quad (3.14)$$

Demand constraints:

$$R_{i,k} = R_{i,k}^0 + x_{i,k} - v_{i,k}, \quad \forall i, \forall k \quad (3.15)$$

$$z_{j,k} = \Delta_{j,k} \left(\sum_{i=1}^I v_{i,k} \right), \quad \forall i, \forall j, \forall k \quad (3.16)$$

Inventory balance constraints:

$$B_{j,k,\xi} + D_{j,k,\xi} = s_{j,k,\xi} + L_{j,k,\xi} + B_{j,k}^0, \quad \forall j, \forall k \quad (3.17)$$

$$L_{j,k,\xi} = \gamma_{j,k} (D_{j,k,\xi} + B_{j,k,\xi} - s_{j,k,\xi}), \quad \forall j, \forall k \quad (3.18)$$

$$F_{j,k,\xi} = F_{j,k}^0 + z_{j,k} - s_{j,k,\xi}, \quad \forall j, \forall k \quad (3.19)$$

Sales, demand and production balance constraints:

$$s_{j,k,\xi} \leq z_{j,k}, \quad \forall j, \forall k \quad (3.20)$$

$$s_{j,k,\xi} \leq D_{j,k,\xi}, \quad \forall j, \forall k \quad (3.21)$$

$$x_{i,k}, z_{j,k}, D_{j,k}, v_{i,k}, s_{j,k,\xi}, R_{i,k}, F_{j,k}, \theta_{i,k}, L_{j,k}, B_{j,k} \geq 0, \quad \forall i, \forall j, \forall k \quad (3.22)$$

Equation 3.13 ensures the amount of raw materials supplied not exceeding the amount available from the source.

Equation 3.14 is the amount of raw materials consumed not exceeding the amount of raw materials available.

Equation 3.15 and 3.16 are the demand balance constraint and the lost sales with backlog constraint.

Equations 3.17 to 3.19 are the material balance for the raw materials, end products and the conversion flow for the finished goods.

Equation 3.20 and 3.21 ensure that the amount of finished products sold should be less than or equal to the amount produced and the demand respectively.

Equation 3.22 makes sure the raw material purchased, the amount of products produced and the end products demand are always non-negative.

3.5.1. Demand and price uncertainties

Demand and price uncertainties are the main types of uncertainties that affect the operations of the supply chain. The end products' demands of the system are random variables with known probability distributions. The normal distributions are used to model the uncertain demands.

Price uncertainty defines the chance or speculation that price of a product might change with respect to time. In this paper, GBM is used to model the uncertain prices of the end products. The GBM is a continuous-time stochastic process in which the logarithm of the randomly varying quantity follows a random movement (Pederson and Zou, 2009). It is used in mathematical finance to model stock prices in the Black–Scholes model (Rodrigo, Erick, Casey, and Richards, 2008). Commodity prices, such as oil or ethanol, are continuous and can be modeled by using this equation. A scenario generation is developed for the price of the finished products. The prices of all three products follow the GBM. This is to reflect the present trading models for commodity. The basic Brownian motion equation is given below:

$$\frac{dS_t}{S_t} = \mu dt + \sigma dz \quad (3.23)$$

The commodity price at time t is represented by a mean value (μ), and volatility (σ). The spot price at a time t is expressed as S_t . The term z is a Wiener process, where, $dz = \varepsilon \sqrt{dt}$ and ε is the uncertain term (Hull and Basu, 2005). The term dt represents the change in time. All terms are derivatives and not partial derivatives. Scenarios are generated by using the derived form of equation 3.23 as shown below:

$$S_t = S_0(1 + \mu dt + \varepsilon \sigma \sqrt{dt}) \quad (3.24)$$

3.6. Proposed solution: Benders decomposition with Monte Carlo simulation

Stochastic programming models that rely on scenarios are often computationally very demanding because their model size increases exponentially as the number of scenarios increase (Fenqui, John, and Grossmann, 2009). Therefore, an effective algorithm is needed to overcome the computational challenges.

Benders decomposition is able to solve large scale mathematical programming, especially in stochastic cases given a certain block structure. Problems are divided into master and sub-problems, where the master problem contains the deterministic part, and the sub-problem has the stochastic part. When solving the sub-problem, Monte Carlo simulation technique is applied to general random scenarios. The sub-problem and the master problem are presented as following:

Sub-problem:

$$\text{Min Sub - opt} = -\sum_{j=1}^J \sum_{\xi=1}^N \sum_{k=1}^K p_{\xi} P_{j,k,\xi} s_{j,k,\xi} + \sum_{j=1}^J \sum_{\xi=1}^N \sum_{k=1}^K p_{\xi} h_{j,k} F_{j,k,\xi} + \sum_{k=1}^K \sum_{\xi=1}^N \sum_{j=1}^J p_{\xi} m_{j,k} L_{j,k,\xi} + \sum_{k=1}^K \sum_{\xi=1}^N \sum_{j=1}^J p_{\xi} q_{j,k} B_{j,k,\xi} \quad (3.25)$$

Where Sub-opt is the value of the objective function of the sub-problem. Here, the objective function is transferred to minimization problem. Therefore, the revenue is negative and the cost positive.

s.t.

Sub-problem constraints:

$$s_{j,k,\xi} + L_{j,k,\xi} - B_{j,k,\xi} = D_{j,k,\xi} - B_{j,k}^0 \quad \forall j, \forall k \quad (3.26)$$

$$\gamma_{j,k} s_{j,k,\xi} - \gamma_{j,k} B_{j,k,\xi} = \gamma_{j,k} D_{j,k,\xi} - L_{j,k}^0 \quad \forall j, \forall k \quad (3.27)$$

$$z_{j,k} + F_{j,k,\xi} - s_{j,k,\xi} = F_{j,k}^0 \quad \forall j, \forall k \quad (3.28)$$

$$z_{j,k} - s_{j,k,\xi} - slk1 = 0, \quad \forall j, \forall k \quad (3.29)$$

$$s_{j,k,\xi} + slk2 = D_{j,k,\xi}, \quad \forall j, \forall k \quad (3.30)$$

$$x_{i,k} > z_{j,k}, D_{j,k}, v_{i,k}, s_{j,k,\xi}, R_{i,k}, F_{j,k}, \theta_{i,k}, L_{j,k}, B_{j,k} \geq 0, \quad \forall i, \forall j, \forall k \quad (3.31)$$

Equation 3.26-Equation 3.30 can be written in the form of $D_\xi y_\xi = h_\xi - B_\xi z_{j,k}$ where, y_ξ constitute the decision variables in the sub-problem which are $s_{j,k,\xi}$, $F_{j,k,\xi}$, $L_{j,k,\xi}$, and $B_{j,k,\xi}$. The terms D_ξ and B_ξ are the recourse and technical matrixes of the sub-problem decision variables. Finally, h_ξ is the right hand side of the sub-problem constraints.

Master problem:

$$\text{Min Optm} = \sum_{i=1}^I \sum_{k=1}^K y_{i,k} x_{i,k} + \sum_{i=1}^I \sum_{k=1}^K \tau_{i,k} d_{i,k} x_{i,k} + \sum_{k=1}^K \sum_{c=1}^C \tau_{k,c} d_{k,c} z_{j,k} + \sum_{i=1}^I \sum_{k=1}^K h_{i,k} R_{i,k} + \sum_{i=1}^I \sum_{k=1}^K \beta_{i,k} v_{i,k} + \eta \quad (3.32)$$

Where Optm is the value of the objective function of the master problem.

s.t.

Master problem constraints:

$$x_{i,k} \leq \theta_{i,k}, \quad \forall i, \forall k \quad (3.33)$$

$$v_{i,k} \leq x_{i,k}, \quad \forall i, \forall k \quad (3.34)$$

$$R_{i,k} = R_{i,k}^0 + x_{i,k} - v_{i,k}, \quad \forall i, \forall k \quad (3.35)$$

$$z_{j,k} = \Delta_{j,k} \left(\sum_{i=1}^I v_{i,k} \right), \quad \forall i, \forall j, \forall k \quad (3.36)$$

$$\eta \geq \frac{1}{N} \sum_{\xi=1}^N \pi_\xi (h_\xi - B_\xi z_{j,k}) \quad (3.37)$$

Equation 3.37 is the optimality cut. The term $p_\xi = 1/N$ is the probabilities of the scenarios generated. New terms $slk1$ and $slk2$ are introduced. The first term is the slack that is added to the amount produced to balance the sales amount or the constraint. The second slack is added to the amount sold to ensure it is equal to the amount of end products produced. All other parameters and variables have their usual meanings as defined previously.

The Benders decomposition with Monte Carlo simulation algorithm is as follows:

Step 1. Set $l=1$, where l is the iteration counter, and $UB_l = \infty$, that is, upper bound is set to positive infinity, and the lower bound is set to zero, $LB_l = 0$. Solve problem Equation 3.32- Equation 3.36 and let $\eta=0$ to obtain the optimal decision values of the master problem without cut.

- Step 2. Use Monte Carlo method to generate N samples for the demand and price data by using the normal distribution and GBM respectively for all the end products.
- Step 3. Solve the sub problem Equation 3.25-Equation 3.30 by using $z_{j,k}$, as a constant to obtain the optimal decisions $s_{j,k,\xi}$, $F_{j,k,\xi}$, $L_{j,k,\xi}$, and $B_{j,k,\xi}$.
- Step 4. Determine the dual of the sub problem, and represent them by the dual variables, in this case: π_{ξ}
- Step 5. Update the upper bound by setting: $UB_{l+1} = \min\{UB_l, Optm + (Sub - opt)\}$
- Step 6. Update the lower bound problem by using: $LB_{l+1} = Optm$
- Step 7. Add Equation 3.37 to the master problem.
- Step 8. Proceed to test if $(UB_l - LB_l) < Tolerance$ return the optimal solution, otherwise, set the iteration counter to $l=l+1$. Here Tolerance is a pre-determined small value to determine the stopping criterion.
- Step 9. Solve the updated master problem Equation 3.32-Equation 3.37 and add the updated cut η and go back to step 3.

3.7. Case study

In this section, numerical studies are conducted to demonstrate the effectiveness of the proposed solution. The application of the model is based on a proposed bioethanol supply chain in North Dakota, USA. The problem is solved using MATLAB and GAMS programs on a Sony Viao Laptop of 5GB RAM, and processor speed of 3.5GHz.

3.7.1. Configuration of the biofuel supply chain

The supply chain consists of four biomass supply sources, two biorefinery plants, and two distribution centers. The four biomass raw material sources can supply biomass to either of the two biorefinery plants. Raw materials are transported by truck to the biorefinery plants. The biorefinery plants produce ethanol, corn oil and DDGS. The major end product is ethanol. The end products that are produced are also transported from the biorefinery plants to the distribution centers. Major decisions such as the amount of raw materials purchased, and the amount of end products produced are considered. The objective is to maximize the expected profit of the entire system network considered. Figure 3 shows the ethanol supply chain network which is used for the case study.

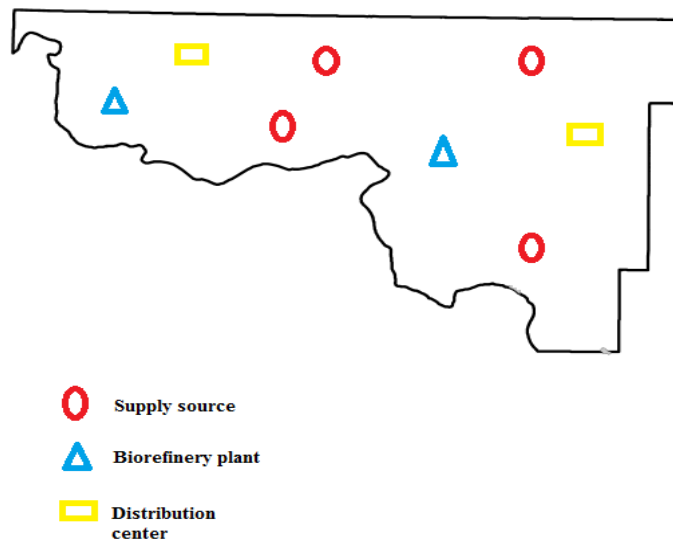


Figure 3. The configuration of bioethanol supply chain in case study

3.7.2. Summary of parameters

Parameters such as prices of end products demand of end products, capacities of biorefinery plants and other parameters such as unit raw material cost, transportation cost and backlog costs are summarized in Table 9. The prices of end products follow Geometric Brownian Motion (GBM). The demands of end products follow normal probability distribution.

Table 9. Parameters for the case study

Parameters	Values	Units
Price of ethanol	GBM (2.25,0.95)	\$ (dollars)
Price of corn oil	GBM (0.415,0.95)	\$ (dollars)
Price of DDGS	GBM (0.085,0.95)	\$ (dollars)
Ethanol demand	N(7,800,000, 1717.8)/month	Gallons
Corn oil demand	N(4,800,000, 1118.3)/month	Pounds
DDGS demand	N(1,500,000, 741.6)/month	Tons
Capacity of plant 1	15,000,000	Bushels
Capacity of plant 2	15,000,000	Bushels
Unit cost per raw material purchased	6.8/bushel	\$ (dollars)
Unit raw material transportation cost to plants	2.158/mile / bushel	\$ (dollars)
Unit end products transportation cost	2.158/mile/ amount produced	\$ (dollars)
Unit inventory holding cost for raw material	0.005/bushel	\$ (dollars)
Unit inventory holding cost for finished goods	0.005/gallon, tons, pounds	\$ (dollars)
Unit penalty cost for unmet demand	0.005/gallon, tons, pounds	\$ (dollars)
Unit cost for backlog demand	0.005/gallon, tons, pounds	\$ (dollars)
Unit cost per processing	1.24/bushel	\$ (dollars)
Fraction of unmet demand	0.05/gallon, tons	\$ (dollars)

3.7.3. Solutions comparison and sensitivity analysis

The proposed model Equation 3.25-3.37 is solved by using Benders decomposition with Monte Carlo simulation Algorithm coded in GAMS. The samples of end products' demands are generated according to normal distributions. Figures 4, 5, and 6 are sample time series graphs for the end products prices generated using MATLAB according to the Geometric Brownian Motion (GBM). The deterministic model Equation 3.1 - 3.11 is solved by the linear programming solver provided by GAMS. The solution results are imputed to simulation model to obtain expected profit.

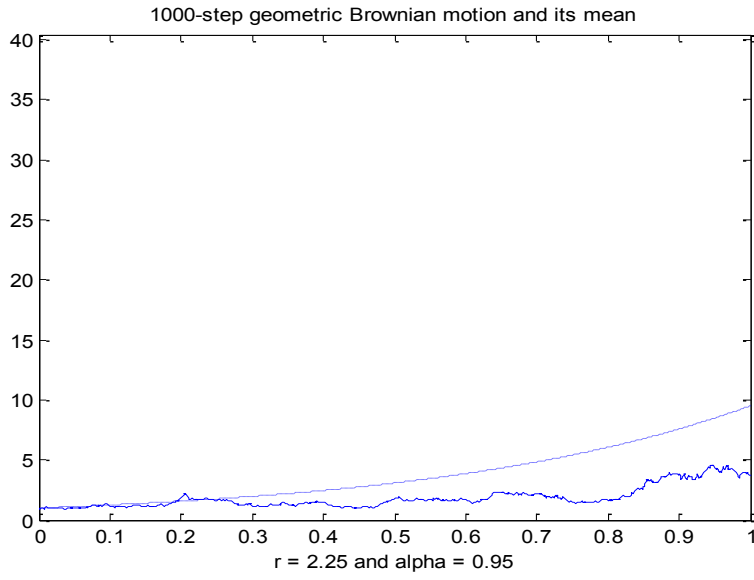


Figure 4. A scenario generation for ethanol price

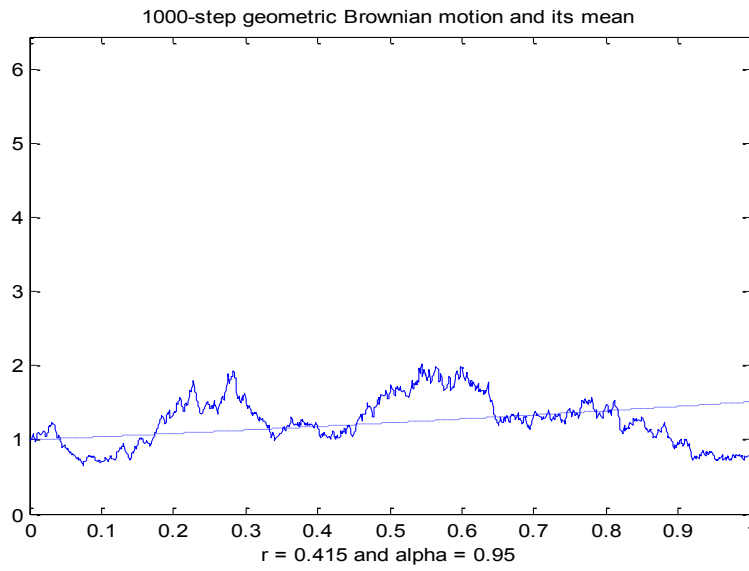


Figure 5. A scenario generation for corn oil price

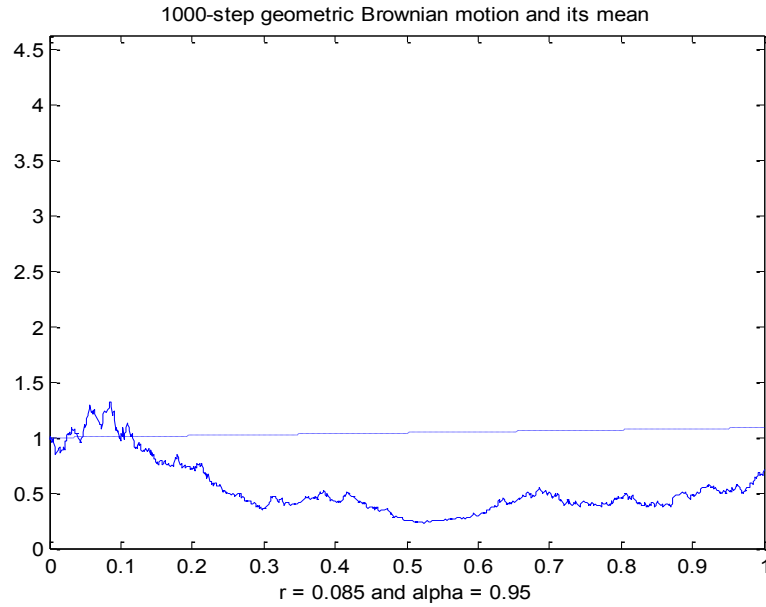


Figure 6. A scenario generation for DDGS price

3.7.3.1. Solution comparison

Firstly, case 1 studies the different performance between deterministic model and proposed model by considering different demand uncertainties. Different scenarios have been studied. Scenario 3 is the base case which uses the data shown in Table 9. Scenarios 0, 1 and 2 are 15%, 10%, and 5% decrement in demand variance of base case respectively. Scenarios 4, 5, and 6 are 5%, 10%, and 15% increment in demand variance of base case respectively. The summary of the results are shown in Table 10 and Figure 7.

Table 10. Comparison of deterministic and stochastic profits for demand variance (Case 1)

Scenario	Expected profit (\$)		Profit change (%)
	Deterministic model	Stochastic model	
Scenario 0	13,268,600.00	15,169,200.00	14.32
Scenario 1	13,528,100.00	15,192,400.00	12.3
Scenario 2	13,787,600.00	15,135,500.00	11.74
Scenario 3	13,009,100.00	15,168,600.00	16.6
Scenario 4	12,749,600.00	14,910,500.00	16.95
Scenario 5	12,490,100.00	14,652,300.00	17.31
Scenario 6	12,230,500.00	14,394,100.00	17.69

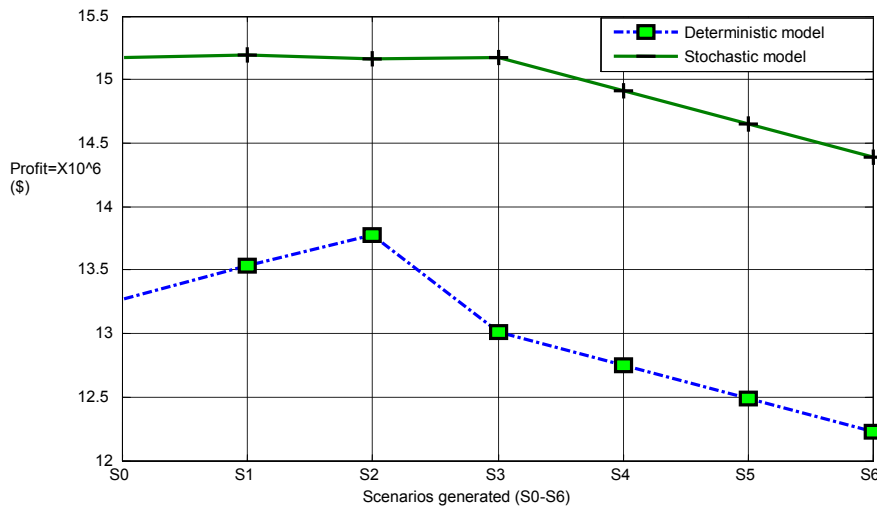


Figure 7. Profit variations for changes in demand variance

The results for case 1 show that the profit in the stochastic method improves by 14.32%, 12.30%, and 11.74% when the demand variance is decreased by the respective percentages provided, that is 15%, 10%, and 5%. Similarly, profit of proposed method is 16.95%, 17.31%, and 17.69% higher than that of deterministic method, when the demand variance increases 5%, 10%, and 15% in respectively. The results show that the performance of proposed model is better than deterministic model.

Secondly, case 2 studies the different performance between deterministic model and proposed model by changing the price volatility of end products. Similarly, Scenario 3 is the base case which uses the data shown in Table 11. Scenarios 0, 1 and 2 are 15%, 10%, and 5% decrement in price volatility of base case respectively. Scenarios 4, 5, and 6 are 5%, 10%, and 15% increment in price volatility of base case respectively. Table 3 and Figure 6 show the comparison results.

Table 11 and Figure 8 show the comparison results. The results indicate that although when price uncertainty increases expected profits for both models decrease. However, proposed model performs better in all the six scenarios. Case 1 and case 2 implies that when uncertainties exist, proposed model performs better than deterministic model.

Table 11. Comparison of deterministic and stochastic models for price uncertainties (Case 2)

Scenario	Expected Profit (\$)		Profit change (%)
	Deterministic model	Stochastic model	
Scenario 0	17,500,800.00	19,656,700.00	12.32
Scenario 1	15,156,650.00	18,037,700.00	19.01
Scenario 2	14,967,800.00	16,950,000.00	13.24
Scenario 3	13,009,100.00	15,168,600.00	16.60
Scenario 4	12,537,200.00	14,262,000.00	13.76
Scenario 5	10,500,800.00	12,007,600.00	14.35
Scenario 6	8,978,110.00	9,394,830.00	4.64

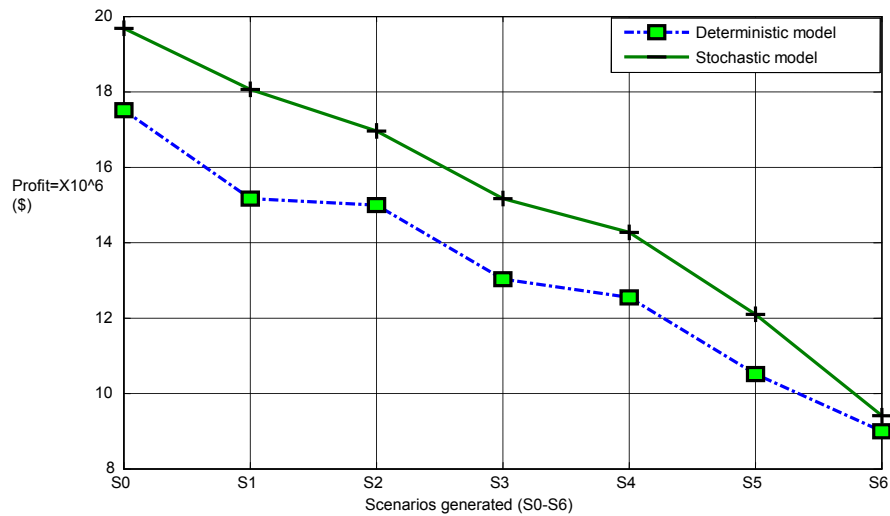


Figure 8. Percentage profit variations for change in price

3.7.3.2. Price-sensitive demand analysis

Furthermore, price-sensitive demand is applied to the proposed model and analysis is conducted to better understand the relationship of the uncertainties. Price-sensitive demand can be modeled as either additive or multiplicative (Sajadieh and Jokar, 2009). In this study, we adapt the additive model which is given by $d(p) = \alpha - \beta p$, where α is constants, and β is the slope of the demand curve function. The terms $d(p)$ and p represent the price-sensitive demand and price respectively. The analysis conducted considered only the ethanol price variation, since it has the largest contribution to the profit. Reasons such as price of gasoline, consumption rate per mileage, tax subsidy and annualized capital cost will make it difficult to sell ethanol above and below certain price. Therefore, the study focuses on the price range from \$1.75 to \$3.5. Table 12 and Figure 9 show the relationship of expected profits and the mean price of biofuel.

Table 12. Demand price sensitivity analysis

a	b	Mean price (\$)	Expected profit (\$)	Demand (d)
19500000	5200000	3.50	9,211,072.67	1300000
19500000	5200000	3.25	10,209,979.21	2600000
19500000	5200000	3.00	11,825,429.00	3900000
19500000	5200000	2.75	13,725,943.00	5200000
19500000	5200000	2.50	15,057,625.00	6500000
19500000	5200000	2.25	15,168,600.00	7800000
19500000	5200000	2.00	12,744,852.00	9100000
19500000	5200000	1.75	9,076,383.00	10400000

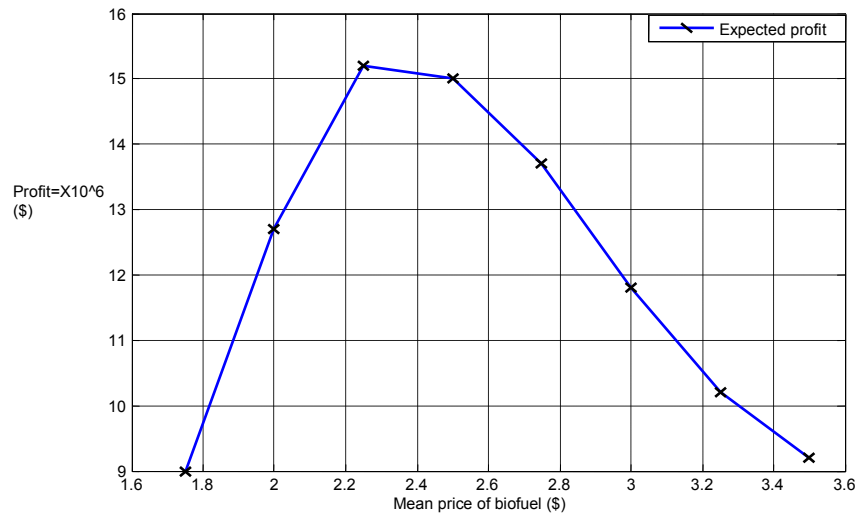


Figure 9. Analysis of demand price sensitivity

It can be seen from Figure 9 that the supply chain is most profitable if the ethanol price is between \$2.25 and \$2.50 for this analysis. This confirms the fact established that factors, such as biofuel plant capital costs, subsidies, and gasoline price will hinder the decision to sell and produce ethanol at certain price and cost respectively.

3.7.4. Cost distribution

Figure 10 shows the cost distribution of the base case for the entire supply chain. The results show that the largest cost factor is due to raw material purchase, which accounts for 36%

of the total cost. Also, costs such as production accounts for the second largest, which is 27%. Finally, end product and raw material (RM) transportation costs account for 20% and 17% of the total cost respectively.

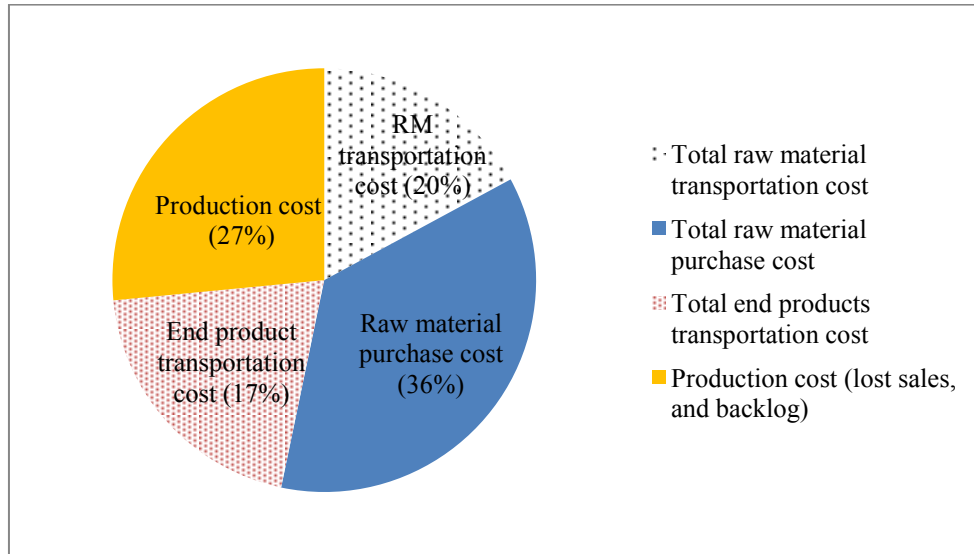


Figure 10. Percentage contribution of cost parameters

3.8. Conclusions and further research

In this section, a stochastic linear programming model for the production planning of a multi-product biofuel supply chain is developed. Demands of end products follow normal distributions with known mean and standard deviation, and Geometric Brownian Motions (GBMs) are used to model the price uncertainties of end products. A bender’s decomposition with Monte Carlo simulation algorithm is applied to solve the proposed model.

The case studies based on a biofuel supply chain in North Dakota are conducted to test the effectiveness and efficiency of the proposed model. The results of proposed stochastic model outperform the results of deterministic model based on the simulation analyses. Sensitivity analyses are performed to gain management insight regarding the uncertainties.

The proposed model can be applied in any biomass based biofuel supply chain. In order to establish a robust biofuel supply chain, more issues should be considered in the future research. Therefore, the extension of the research will be focused on 1) considering more uncertainties, such as uncertainties of raw materials supply, production, and transportation, in the model (Awudu and Zhang, 2012); 2) incorporating disruptions, such as disruptions of raw material supply and demands, in the model (Khor, Elkamel, Ponnambalam, and Douglas, 2008; Zhou et al., 2010); and 3) considering the sustainability concepts and including environmental and social performance measurements in the model (Behrangrad, Sugihara, and Funaki, 2011; Wu, Liu, Han, and Wei, 2011; Yu and Tao, 2009).

CHAPTER 4: OPTIMIZING A HYBRID-GENERATION BIOFUEL SUPPLY CHAIN DECISIONS UNDER UNCERTAINTIES BY CONSIDERING HEDGING STRATEGIES

4.1. Abstract

Integrating hedging decisions is important in any supply chain setting to reduce unwanted variations in expected profit or cost. This section of the dissertation develops a two-stage stochastic linear programming model that uses hedging strategies to optimize decisions for a hybrid-generation biofuel supply chain (HGBSC) setting. The HGBSC network consists of feedstock supply sources, warehouses, biorefinery plants, and demand zones. Corn and cellulosic feedstocks are the two main input raw materials. Biorefineries can purchase corn through futures and cellulosic through spot price, while the ethanol end-product sale is hedged using futures. The hedging strategy is used when the price of corn feedstock exceeds certain percentage of the average price per scenario. The Multi-cut Benders Decomposition Algorithm is used to solve the resulting model. This part of the dissertation is structured by first developing an optimization problem which considers maximization of the supply chain profit under risk without hedging for both corn and cellulosic biorefinery plants. Secondly, similar profit maximization is considered under risk with hedging. Thirdly, prices of corn feedstock and ethanol end-products which follow a mean reversion (MR) are modeled as uncertain parameters in the problem. Fourth, a representative HGBSC using an integrated biofuel setting in North Dakota is used for this study. The results for both hedging and non-hedging models are compared for profit realizations. Further sensitivity analyses of profit based on different parameter changes are conducted.

4.2. Introduction

The capability to improve supply chain responsiveness in meeting uncertainties is critical in today's global supply chain setting. Uncertainties in the biofuel supply chain are realized in

every stage of the decision making process, therefore making it an important aspect of the value chain. Some of the uncertainties in the HGBSC include, but not limited to: (1) price of ethanol, (2) cost of feedstock, (3) transportation cost of raw materials and end-products, (4) conversion rate, (5) production cost, and (6) demand of end-product. Not incorporating uncertainties in the biofuel supply chain decision making results in profit variation from the expected or targeted profit.

Since these uncertainties introduce significant risk in the decision making process, there is the need to hedge against these risks. Hedging is a mechanism used to reduce profit or cost variation that is inherent in commodities or stocks open positions. The purpose of hedging is to reduce the variability of a product price or cost (Heging mechanism, 2000). It is used to protect portfolio volatility due to market fluctuation during budget, economic, and political or corporate turmoil. The basic rule in hedging is that the risk of a loss in any portfolio is offset by the gains in the futures or options position in which the same commodity or its derivative is sold or purchased. Although there are many kinds of risks within the supply chain, operational and financial risks are frequently discussed. Examples of some of these risks are supply, demand, process, commitment, intellectual property, behavioral, economic, and political risks. These risks can be categorized into financial, operational, marketing, corporate, and other types of risks.

Research in risk management, especially hedging in biofuel supply chain is limited. This makes it important to develop optimization models that effectively integrate hedging decisions in the supply chain decision process. The hybrid model for hedging provides advantages such as flexibility for multiple supply sources and low cost for cellulosic feedstock. The importance is to provide supply chain visibility and managed expectations of profits or cost. Therefore the direction of this part of the dissertation is to develop an optimization model that incorporates

hedging decisions in the HGBSC. Research novelties such as: 1) developing a heuristic method for the hedging; 2) modeling the corn feedstock and ethanol price uncertainties as Mean Reversion (MR); and 3) developing a hybrid biorefinery supply chain which consists of corn and cellulosic feedstock biorefinery plants. The next section reviews the relevant literature in hedging.

Hedging strategies are employed through some form of transactions designed to minimize exposure to an unwanted business risks (Huchzermeier and Cohen, 1996). The first part of the literature in this dissertation considers the application of financial hedging tools in a supply chain setting. Li, Ritchken, and Wang (2009) investigate the role of forward commitments and option contracts between a seller (supplier) and a buyer (retailer) in the presence of asymmetric information options contracts. The objective is to optimize supplier selection to hedge against these disruptions by using a two-stage stochastic program. Results from the case study indicate an effective trade-off between cost and risk by supporting improved decision making. Financial hedging strategies as defined and illustrated in Yun, Kim, Park, and Park (2009) for use in an integrated biorefinery process to tackle the issue of diversifying products as well as raw materials. The objective of the paper is to minimize the purchase risk of raw materials by using futures contract. The results indicate decreasing profit variability and increasing refinery operational flexibility. Similar approach with a discussion on the advantages of real options in resourcing partners contingent on demand and/or exchange rate scenarios are illustrated in Bish and Suwandechochai (2010). Arnold and Minner (2011) use a forward hedging supply strategy that employs an option pricing framework for demand and market uncertainties. The paper's objective is to adopt a stochastic programming for both linear and non-linear solution to investigate the performance of the model. The results indicate a better

performance of the stochastic case as compared to the deterministic case. Gupta and Maranas (2003) propose a forward contract and options derivatives to price derivatives like the European options. The paper uses a stochastic framework and solves the problem using different algorithms. The results indicate a more stable approach or cost minimization using emission cost with uncertainty than without uncertainties. Additionally, other hedging based on operational hedging perspectives are discussed in Chen and Lin (2009), Goyal and Netessine (2007), Harrison and Van Mieghem (1999), Li and Wang (2010), and Sting and Huchzermeier (2012).

Even though substantial literature has been developed in hedging for other supply chain settings, very little effort has been made in proposing an integrated risk management approach in the biofuel supply chain. Some of the work that has integrated hedging in the decision process in other supply chains includes Kogut and Kulatilaka (1994). This paper examines options under financial and operational hedging scenario. A stochastic dynamic programming approach is used where the uncertain exchange rate is assumed to follow a diffusion process. Options are then used to model the process design and manufacturing. The paper concludes with a balanced hedging result for both the operational and financial hedge with a bias towards the financial hedging approach. Although papers such as Inderfurth and Kelle (2011), Li and Huang (2009), Wu and Chuang (2010), and Mansoornejad, Chambost and Stuart (2010) have discussed other combined hedging methods in a way, none has been contributed within the biofuel supply chain.

The rest of these sections of the dissertation are organized as follows. Section 4.3 presents the problem statement. Section 4.4 provides the mathematical model, generating the price uncertainties, and evaluating the uncertainty parameters. In section 4.5, the solution technique used is outlined. Section 4.6 presents the case study. Sections 4.7 and 4.8 discuss the

uncertainty modeling and the results and analyses. Final conclusions and further research are outlined in section 4.9.

4.3. Problem statement

In this part of the dissertation, a hybrid-generation biofuel supply (HGBSC) chain is studied. There are two types of biomass feedstock considered: first generation and second generation. The representative supply chain diagram for both the cellulosic and corn feedstock is illustrated in Figure 11. The first generation consists of corn and the second generation cellulosic feedstock. The supply chain network consists of raw material supply sources, warehouses or pre-treatment facilities, biorefinery plants, and demand zones. Supply sources are responsible for providing the raw materials which are corn and cellulosic feedstock. Warehouse or pre-treatment facilities prepare the raw materials into a suitable form before being transported to the biorefinery plants. The biorefinery plants convert the pre-treated raw materials into end-products, which is biofuel. The demand zones are aggregated at the county levels. There are i_c number of raw material sources for corn feedstock, and i_m sources for cellulosic feedstock. Warehouse or pre-treatment plants for the respective feedstocks are w_c and w_m . The number of biorefinery plants is k_c for the corn ethanol and k_m for the cellulosic ethanol plants. The end-product which is biofuel is represented by c_e and m_e for corn and cellulosic ethanol respectively. Finally, multi-time period consisting of 12-month horizon is adopted for this work.

Both cellulosic and corn ethanol plants are considered because of the importance of these raw materials to the current biofuel industries. The reason is that the expanded Renewable Fuel Standard (RFS) (referred to as RFS2) requires the annual use of 9 billion gallons of biofuels in 2008. This mandate has been expanded to 36 billion gallons annually in 2022, of which no more than 15 billion gallons can be ethanol from corn starch, and no less than 16 billion must be from

cellulosic biofuels (Ahuja, Magnanti, and Orlin, 1993; Schnepf, 2011; Tang and Tomlin, 2008). This is why it is important to consider both corn and cellulosic feedstock.

Uncertainties such as prices of corn and cellulosic feedstock and prices of end-products are very common in HGBSC. In order to optimize the supply chain decisions, such as the amount of feedstock purchased, biomass pre-treated, amount of ethanol produced, production capacity of biorefinery plants, and the amounts of ethanol shipped from biorefinery to demand points, two-stage stochastic programming models are applied in some research (see for example, Gupta, Maranas, and McDonald, 2000). However, those models do not consider strategies to avoid the risk of having negative or low profit. In order to avoid extreme profit lost, hedging strategy is needed. Therefore, the main objective of this work is to maximize the expected profit within the entire supply chain setting and hedge the risk of obtaining low profit.

Mean reversion models are used to model the prices of the feedstock and end-products. This assumption is used because most commodity prices exhibit high and low prices of for a temporary period, and that the prices will move or shift to the average prices over time (Cecchetti, Lam, and Mark, 1990). This is implemented from the data set obtained from the Iowa University Energy Research Group. The end-products are sold by using futures to reduce profit variability and provide some form of hedging. The corn biomass purchasing mechanism is based on a heuristic hedging strategy since corn as a commodity has high price volatility. In order to reduce the price variability and hedge against future uncertainties, the corn is procured at a futures price. The cellulosic feedstock is purchased at a spot price since no variability is assumed for its price. The heuristic method uses the mean reversion model to generate sample data for both the corn spot and futures prices. Two different samples are picked to authentic the model or ensure fairness. A method of buying corn feedstock using the spot price is used if futures price is

greater than the y times the mean of the n sample price generated. This characterizes a generalized mean of an additional $x\%$ increase in each scenario. Similarly, the future price is opted if the spot price is greater than the y times the mean of the sample price generated.

Two main decisions are presented, no-hedging and hedging. The non-hedging consists of purchasing the feedstock, which is corn and cellulosic raw materials at spot prices. Similarly, the corn and cellulosic ethanol that are produced are sold on the spot market. Meanwhile, hedging involves buying corn feedstock using futures or spot based on the heuristic method developed. At the same time, since cellulosic is traded at the spot price concurrently. Essentially the ethanol produced from both the corn and cellulosic markets are sold using a futures position.

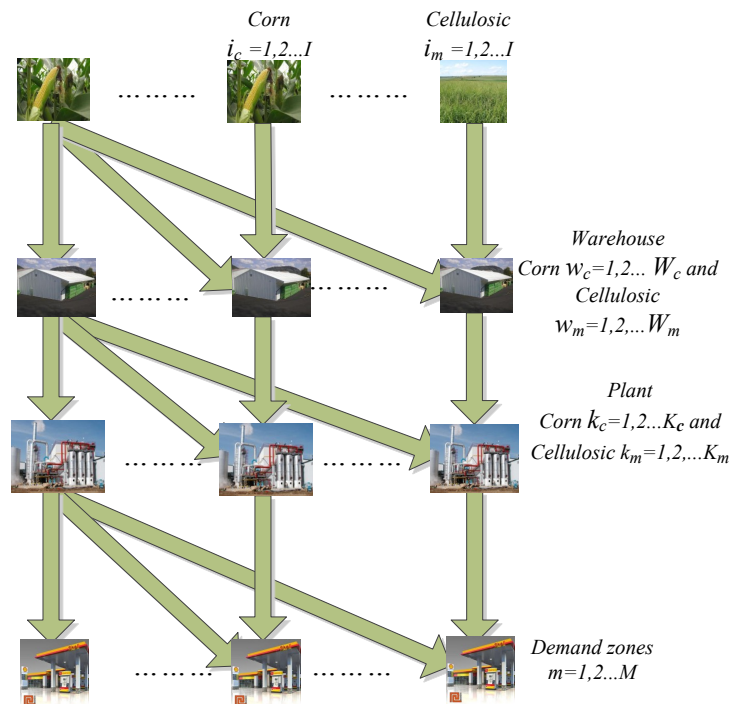


Figure 11. General supply chain structure

4.4. Mathematical model

In this section, a mathematical model is first proposed to incorporate uncertainties without hedging strategy. Secondly, a similar approach is used to develop another mathematical model which comprises risk with hedging strategy. Both models will be solved and compared in the case study to show that the model with hedging strategy reduces risk of reaching extreme low profit. The following presents the indexes of the sets, decision variables, and parameters.

Input variables with and without hedging

Indice/Sets:

i_c	The index of corn feedstock supply source $i_c = 1, 2 \dots I_c$
i_m	The index of cellulosic feedstock supply source $i_m = 1, 2 \dots I_m$
w_c	The index of warehouse for storing corn feedstock $w_c = 1, 2, \dots I_c$
w_m	The index of warehouse for storing cellulosic feedstock $w_m = 1, 2, \dots I_c$
tm	The index of trade market $tm = 1, 2, 3 \dots TM$ (<i>Futures</i>)
cm	The index of cash market $cm = 1, 2, 3 \dots CM$ (<i>Spot</i>)
k_c	The index of corn biorefinery $k_c = 1, 2, 3 \dots KC$
k_m	The index of cellulosic biorefinery $k_m = 1, 2, 3 \dots KM$
c_f	The index of corn feedstock index
c_e	The index of corn ethanol index
m_f	The index of cellulosic feedstock index
m_e	The index of cellulosic ethanol index
t	The index of time horizon for the entire period of planning $t = 1, 2, \dots T$

ξ The index of scenario for the uncertainty

Deterministic parameters

$PC_{k_c, t}$ Production cost of corn ethanol at plant k_c in time period t

$PM_{k_m, t}$ Production cost of cellulosic ethanol at plant k_m in time period t

$H_{c_f, t}^{w_c}$ Inventory holding cost for corn feedstock c_f at warehouse w_c at time period t

$H_{m_f, t}^{w_m}$ Inventory holding cost for cellulosic feedstock m_f at warehouse w_m in period t

$H_{c_e, t}^{k_c}$ Pre-treatment or handling cost for corn feedstock at plant k_c in time period t

$H_{m_e, t}^{k_m}$ Pre-treatment or handling cost for cellulosic feedstock at plant k_c in time period t

F_p Fixed operational cost of the supply chain

V_p Variable operational cost of the supply chain

A_p Annualized cost which includes other cost such as loss of opportunity, human resource

$T_{c_f, t}^{i_c, w_c}$ Transportation cost for corn feedstock c_f from supplier source i_c to warehouse w_c in time period t

$T_{m_f, t}^{i_m, w_m}$ Transportation cost for cellulosic feedstock m_f from supplier i_m to warehouse w_m in time period t

$T_{c_f, t}^{w_c, k_c}$ Transportation cost for corn feedstock c_f from warehouse w_c to biorefinery k_c in time period t

$T_{m_f, t}^{w_m, k_m}$ Transportation cost for cellulosic feedstock m_f from warehouse w_m to biorefinery k_m

	in time period t
$T_{c_e,t}^{k_c,tm}$	Transportation cost for corn ethanol c_e from biorefinery k_c to trade market tm in time period t
$T_{m_e,t}^{k_m,cm}$	Transportation cost for cellulosic ethanol m_e from biorefinery k_m to market tm in time period t
$dc_{c_f,t}^{i_c,w_c}$	Transportation distance for corn feedstock c_f from supply source i_c to warehouse w_c in time t
$dc_{c_f,t}^{w_c,k_c}$	Transportation distance for corn feedstock c_f from warehouse w_c to biorefinery k_c in time period t
$dc_{c_e,t}^{k_c,tm}$	Transportation distance for corn ethanol c_e from biorefinery k_c to trade market tm in time period t
$dm_{m_f,t}^{i_m,w_m}$	Transportation distance for cellulosic feedstock m_f from source i_m to warehouse w_m in time period t
$dm_{m_f,t}^{w_m,k_m}$	Transportation distance for cellulosic feedstock m_f from warehouse w_m to plant k_m in time period t
$dm_{m_e,t}^{k_m,cm}$	Transportation distance for cellulosic ethanol m_e from plant k_m to trade market cm in time period t
β	Corn ethanol conversion rate
λ	Cellulosic ethanol conversion rate
∂_{fl}	Conversion factor from cellulosic feedstock to lignin at refinery plant

∂_{fp}	Conversion factor from cellulosic feedstock to protein at refinery plant
∇_{cd}	Conversion factor from corn feedstock to DDGS at refinery plant
∇_{co}	Conversion factor from cellulosic feedstock to corn oil at refinery plant
W_y	Variable and fixed cost for warehouse cost for both cellulosic and corn feedstock
C_v	Variable and fixed cost for biorefinery cost for both cellulosic and corn ethanol
$d_{c_e,t}^{tm}$	Demand for corn ethanol c_e at trade market tm in time period t
$d_{m_e,t}^{cm}$	Demand for cellulosic ethanol c_m at cash market m_e in time period t
D_t	Total demand for cellulosic and corn ethanol at time period t
$Capf_{wco}^{min}$	Minimum fixed capacity of corn warehouse
$Capf_{wco}^{max}$	Maximum fixed capacity of corn warehouse
$Capf_{wce}^{min}$	Minimum fixed capacity of cellulosic warehouse
$Capf_{wce}^{max}$	Maximum fixed capacity of cellulosic warehouse
$Capf_{kco}^{min}$	Minimum fixed capacity of corn biorefinery plant
$Capf_{kco}^{max}$	Maximum fixed capacity of corn biorefinery plant
$Capf_{kce}^{min}$	Minimum fixed capacity cellulosic biorefinery plant
$Capf_{kce}^{max}$	Maximum fixed capacity cellulosic biorefinery plant
$Capv_{wco}^{min}$	Minimum variable capacity of corn warehouse
$Capv_{wco}^{max}$	Maximum variable capacity of corn warehouse
$Capv_{wce}^{min}$	Minimum variable capacity of cellulosic warehouse

$Capv_{wce}$ max Maximum variable capacity of cellulosic warehouse

$Capv_{kco}$ min Minimum variable capacity of corn biorefinery plant

$Capv_{kco}$ max Maximum variable capacity of corn biorefinery plant

$Capv_{kce}$ min Minimum variable capacity cellulosic biorefinery plant

$Capv_{kce}$ max Maximum variable capacity cellulosic biorefinery plant

Stochastic parameters

$C_{c_f,t}^{\xi,i_c}$ Uncertain cost of purchasing corn feedstock c_f from supplier i_c in time period t under scenario ξ

$P_{c_e,t}^{\xi,tm}$ Price of corn ethanol c_e sold under scenario ξ in time period t to market tm

$C_{m_f,t}^{\xi,i_m}$ Uncertain cost of purchasing cellulosic feedstock m_f from supplier i_m in time period

$P_{m_e,t}^{\xi,tm}$ Price of cellulosic ethanol m_e sold under scenario ξ in time period t to market tm

$Pcd_{c_e,t}^{\xi,tm}$ Price of DDGS

$Pco_{c_e,t}^{\xi,tm}$ Price of corn oil

$Pl_{m,t}^{\xi,cm}$ Price of lignin

$Pp_{m,t}^{\xi,cm}$ Price of protein

First-stage decision variables

$Xc_{c_f,t}^{w_c}$ Capacity of corn warehouse w_c for pre-treating feedstock c_f in time period t

$Xc_{m_f,t}^{w_m}$ Capacity of cellulosic warehouse w_m for pre-treating feedstock m_f in time period t

$Cap_{k_c,t}$ Production capacity of corn ethanol at plant k_c in time period t

$Cap_{k_m,t}$ Production capacity of cellulosic ethanol at plant k_m in time period t

Second-stage decision variables

$x_{i_c,t}^{w_c,\xi}$ Amount of Corn feedstock purchased from source i_c for warehouse w_c at time period t under scenario ξ

$x_{i_m,t}^{w_m,\xi}$ Cellulosic feedstock purchased from source i_m for warehouse w_m at time period t under scenario ξ

$S_{c_e,t}^{\xi,tm}$ Amount of corn ethanol m_e sold in scenario ξ at time t for trade market tm

$S_{m_e,t}^{\xi,tm}$ Amount of cellulosic ethanol m_e sold in scenario ξ at time t for trade market tm

$z_{k_c,t}^{tm,\xi}$ Amount of corn ethanol produced at plant k_c at time period t for trade market tm under scenario ξ

$z_{k_m,t}^{tm,\xi}$ Amount of cellulosic ethanol produced at plant k_m at time t for trade market tm under scenario ξ

$CL_{m_e,t}^{k_m,\xi}$ Amount of lignin produced from cellulosic feedstock at plant k_m in time period t

$CP_{m_e,t}^{k_m,\xi}$ Amount of protein produced from cellulosic at plant k_m in time period t

$CD_{c,t}^{k_c,\xi}$ Amount of DDGS produced from corn at plant k_c in time period t

$CO_{c,t}^{k_c,\xi}$ Amount of corn oil produced from corn at plant k_c in time period t

$Xp_{c_f,t}^{w_c,\xi}$ Pre-treated corn feedstock c_f available at warehouse w_c in time t under scenario ξ

$Xp_{m_f,t}^{w_m,\xi}$ Pre-treated cellulosic feedstock m_f at warehouse w_m in time t under scenario ξ

$Xc_{c_f,t}^{w_c,\xi}$ Variable capacity of corn warehouse w_c for pre-treating feedstock m_c in time t under

scenario ξ

$Xc_{m_f,t}^{w_m,\xi}$ Variable capacity of cellulosic warehouse w_m for in time t under scenario ξ

$Cap_{k_c,t}^{\xi}$ Variable production capacity of corn ethanol at plant k_c in time t under scenario ξ

$Cap_{k_m,t}^{\xi}$ Variable production capacity of cellulosic ethanol at biorefinery k_m in period t
under scenario ξ

Index for hedging strategy

F Denotes futures price symbol used on the trade market

S Denotes spot price symbol used on the trade market

tm Denotes the trade market

cm Denotes the cash market

Hedging strategy decision variables

X The total amount of feedstock needed to be purchased (both corn and cellulosic)

M Dummy variable

$Y_{corn_fut}(\xi)$ Binary decision to buy corn under futures hedging strategy

$Y_{corn_spot}(\xi)$ Binary decision to buy corn under spot hedging strategy

$Y_{cell_fut}(\xi)$ Binary decision to buy cellulosic under futures hedging strategy

$Y_{cell_spot}(\xi)$ Binary decision to buy cellulosic under spot hedging strategy

$X_{c_f,tm}^{F,t}$ The amount of corn feedstock c_f for hedging purchased at futures price F in time t

$X_{m_f,cm}^{S,t}$ The amount of cellulosic feedstock m_f for hedging bought at spot price S in time t

$HZ_{c_e,tm}^{F,t}$ Corn ethanol c_e produced for hedging at time period t for cash market tm

$HZ_{m_e,tm}^{F,t}$ Cellulosic ethanol m_e produced for hedging at time period t for cash market tm

Hedging strategy parameters

$PX_{c_f,tm}^{F,t}$ Futures price of corn feedstock c_f in market tm at time period t at futures price F

$PX_{m_f,cm}^{S,t}$ Spot price of cellulosic feedstock m_f for hedging purchased at spot price S in time t

$Pz_{c_e,tm}^{F,t}$ Futures price for selling corn ethanol c_e when taking the position at time period t at futures market F

$Pz_{m_e,cm}^{F,t}$ Futures price for selling cellulosic ethanol m_e for hedging purchased at spot market S in time period t

$SX_{c_f,tm}^{F,t}$ Spot price of corn feedstock

$Avg(PX_{c_f,tm}^{F,t})$ Average price of corn futures price

cpo Cost of brokerage, margin calls and interest rates for corn future long position

α Heuristic value for hedging strategy

4.4.1. Mathematical model with risk without hedging strategies

This section proposed a two-stage stochastic programming model to considering uncertain purchasing prices without any hedging strategy.

Objective function

The objective function seeks to maximize profit, which is equal to the revenue minus the total cost. The revenue includes the total sales of biofuel and its by-products. The total cost consists of the raw materials purchasing cost, the transportation cost for raw materials and end-

products, warehouse or pre-treatment processing cost, biorefinery processing cost, and the inventory holding costs for both feedstock and end products at the warehouse and biorefinery plants.

Objective function:

$$\begin{aligned} \text{Max } Z_1 = & \text{Rc} + \text{Rce} + \text{Rdgs} + \text{Rco} + \text{Rlig} + \text{Rprot} - \text{Cco} - \text{Ico} - \text{Pco1} - \text{Capco} - \text{Pco2} - \text{Tco1} - \text{Tco2} - \text{Tco3} - \\ & \text{Cce} - \text{Ice} - \text{Pce1} - \text{Capce} - \text{Pce2} - \text{Tce1} - \text{Tce2} - \text{Tce3} - \text{FcVc} \end{aligned} \quad (4.1)$$

Revenue of corn and cellulosic sales

Rc is the revenue obtained by selling corn ethanol c_e at the trade market tm for time period t

$$\text{Rc} = E_{\xi} \left(\sum_{k_c \in KC} \sum_{tm \in TM} \sum_{t \in T} P_{c_e, t}^{\xi, tm} S_{c_e, t}^{\xi, tm} \right) \quad (4.1a)$$

Rce is the revenue obtained by selling cellulosic ethanol m_e at the trade market cm for time period t

$$\text{Rce} = E_{\xi} \left(\sum_{k_m \in KM} \sum_{c_m \in CM} \sum_{t \in T} P_{m_e, t}^{\xi, tm} S_{m_e, t}^{\xi, cm} \right) \quad (4.1b)$$

Rdgs is the revenue obtained by selling DDGS produced at plant k_c sold to cash market cm for time period t

$$\text{Rdgs} = E_{\xi} \left(\sum_{k_c \in KC} \sum_{tm \in TM} \sum_{t \in T} P_{c_d, t}^{\xi, tm} CD_{c, t}^{k_m, \xi} \right) \quad (4.1c)$$

Rco is the revenue obtained by selling corn oil produced at plant k_m , sold at trade market cm at time period t

$$\text{Rco} = E_{\xi} \left(\sum_{k_c \in KC} \sum_{tm \in TM} \sum_{t \in T} P_{c_o, t}^{\xi, tm} CD_{c, t}^{k_m, \xi} \right) \quad (4.1d)$$

Rlig is the revenue obtained by selling lignin produced and sold on the cash market cm for time period t

$$R_{lig} = E_{\xi} \left(\sum_{k_m \in KM} \sum_{tm \in TM} \sum_{t \in T} P_{m_e, t}^{\xi, tm} CL_{m, t}^{k_m, \xi} \right) \quad (4.1e)$$

Rprot is the revenue obtained by selling protein produced sold to the trade market cm at time period t

$$R_{prot} = E_{\xi} \left(\sum_{k_c \in KC} \sum_{tm \in TM} \sum_{t \in T} P_{m_e, t}^{\xi, tm} CP_{m, t}^{k_m, \xi} \right) \quad (4.1f)$$

Costs related to corn-based supply chain

Cco is the cost of corn feedstock purchased from supply source i_c to warehouse w_c at period t

$$C_{co} = E_{\xi} \left(\sum_{w_c \in WC} \sum_{t \in T} C_{c_f, t}^{i_c, \xi} x_{i_c, t}^{w_c, \xi} \right) \quad (4.1g)$$

Ico is the fixed and variable inventory holding cost for corn feedstock c_f at warehouse w_c at time period t

$$I_{co} = E_{\xi} \left(\sum_{w_c \in WC} \sum_{t \in T} W_v X_{c_f, t}^{w_c, \xi} \right) + \sum_{w_c \in WC} \sum_{t \in T} H_{c_f, t}^{w_c} X_{c_f, t}^{w_c} \quad (4.1h)$$

Pco1 is the pre-treatment cost of corn feedstock at the warehouse for the time period t

$$P_{co1} = E_{\xi} \left(\sum_{k_c \in KC} \sum_{t \in T} H_{c_e, t}^{k_c} X_{c_f, t}^{w_c} \right) \quad (4.1i)$$

Capco is the fixed and variable capacity cost for corn ethanol production in time period t

$$C_{apco} = E_{\xi} \left(\sum_{w_c \in WC} \sum_{t \in T} C_v Cap_{k_c, t}^{\xi} \right) + \sum_{w_c \in WC} \sum_{t \in T} H_{c_f, t}^{w_c} Cap_{k_c, t} \quad (4.1j)$$

Pco2 is the cost of production of corn ethanol c_e at plant k_c in time period t

$$Pco2 = E_{\xi} \left(\sum_{k_c \in KC} \sum_{t \in T} PC_{k_c, t} z_{k_e, t}^{tm, \xi} \right) \quad (4.1k)$$

Tco1 is the transportation cost of corn feedstock from supply source i_c to warehouse w_c

$$Tco1 = E_{\xi} \left(\sum_{i_c \in IC} \sum_{w_c \in WC} \sum_{t \in T} T_{c_f, t}^{i_c, w_c} dc_{c_f, t}^{i_c, w_c} x_{i_c, t}^{w_c, \xi} \right) \quad (4.1l)$$

Tco2 is the transportation cost of corn feedstock from warehouse w_c to biorefinery k_c

$$Tco2 = E_{\xi} \left(\sum_{w_c \in WC} \sum_{k_c \in KC} \sum_{t \in T} T_{c_f, t}^{w_c, k_c} dc_{c_f, t}^{w_c, k_c} xp_{c_f, t}^{w_c, \xi} \right) \quad (4.1m)$$

Tco3 is the transportation cost of corn ethanol from biorefinery k_c to trade market tm in time t

$$Tco3 = E_{\xi} \left(\sum_{k_c \in KC} \sum_{tm \in TM} \sum_{t \in T} T_{c_e, t}^{k_c, tm} dc_{c_e, t}^{k_c, tm} z_{k_c, t}^{tm, \xi} \right) \quad (4.1n)$$

Costs related to cellulosic-based supply chain

Cce is the total cost of cellulosic feedstock that are purchased from supply source i

$$Cce = E_{\xi} \left(\sum_{w_m \in WM} \sum_{t \in T} C_{m_f, t}^{i_m, \xi} x_{i_m, t}^{w_m} \right) \quad (4.1o)$$

Ice is the fixed and variable inventory holding cost for cellulosic feedstock which is given by

$$Ice = E_{\xi} \left(\sum_{w_m \in WM} \sum_{t \in T} W_v Xc_{m_f, t}^{w_m, \xi} \right) + \sum_{w_m \in WM} \sum_{t \in T} H_{m_f, t}^{w_m} Xc_{m_f, t}^{w_m} \quad (4.1p)$$

Pce is the pre-treatment or holding cost of cellulosic feedstock at the warehouse

$$Pce = E_{\xi} \left(\sum_{k_m \in KM} \sum_{t \in T} H_{m_e, t}^{k_m} Xc_{m_f, t}^{w_m} \right) \quad (4.1q)$$

Cce is the fixed and variable capacity cost for corn ethanol production in time period t

$$Cce = E_{\xi} \left(\sum_{w_c \in WC} \sum_{t \in T} C_v Cap_{k_m, t}^{\xi} \right) + \sum_{w_c \in WC} \sum_{t \in T} H_{c_f, t}^{w_c} Cap_{k_m, t} \quad (4.1r)$$

Pce1 is the cost of cellulosic production for the entire particular time period which is given by

$$Pce1 = E_{\xi} \left(\sum_{k_m \in KM} \sum_{t \in T} PC_{k_m, t} z_{k_m, t}^{tm, \xi} \right) \quad (4.1s)$$

Tce1 is the transportation cost of cellulosic feedstock from supply source to warehouse w_m is

$$Tce1 = E_{\xi} \left(\sum_{i_m \in IM} \sum_{w_m \in WM} \sum_{t \in T} T_{m_f, t}^{i_m, w_m} dc_{m_f, t}^{i_m, w_m} x_{i_m, t}^{w_m, \xi} \right) \quad (4.1t)$$

Tce2 is transportation cost of cellulosic feedstock from warehouse to biorefinery k

$$Tce2 = E_{\xi} \left(\sum_{w_m \in WM} \sum_{k_m \in KM} \sum_{t \in T} T_{m_f, t}^{w_m, k_m} dc_{m_f, t}^{w_m, k_m} Xp_{m_f, t}^{w_m, \xi} \right) \quad (4.1u)$$

Tce3 is transportation cost of cellulosic ethanol from biorefinery to demand zones

$$Tce3 = E_{\xi} \left(\sum_{k_m \in KM} \sum_{cm \in CM} \sum_{t \in T} T_{m_e, t}^{k_m, cm} dc_{m_e, t}^{k_m, cm} z_{k_m, t}^{tm, \xi} \right) \quad (4.1v)$$

FcVc is other costs are variable, annualized, and fixed cost for the entire corn and cellulosic supply chain

$$FcVc = F_p + V_p + C_p \quad (4.1w)$$

Subject to:

Warehouse capacity constraints

Equation 4.2 ensures the total amount of corn feedstock supplied from the sources to the warehouse should be less than or equal to the amount available at the sources

$$\sum_{i_c \in IC} x_{i_c, t}^{w_c, \xi} \leq Xp_{c_f, t}^{w_c, \xi} \quad \forall i_c, \forall w_c, \forall c_f, \forall \xi, \forall t \quad (4.2)$$

Equation 4.3 ensures the total amount of cellulosic feedstock supplied from the source to the warehouse should be less than or equal to the amount available at the sources

$$\sum_{i_m \in IM} x_{i_m, t}^{w_m, \xi} \leq Xp_{m_f, t}^{w_m, \xi} \quad \forall i_m, \forall w_m, \forall m_f, \forall \xi, \forall t \quad (4.3)$$

Demand, sales, capacity and production constraints

Equation 4.4 ensures the amount of corn ethanol sold to each trade market cannot be more than the market demand at a given time period.

$$S_{c_e, t}^{\xi, tm} \leq d_{c_e, t}^{tm, \xi} \quad \forall c_e, \forall tm, \forall \xi, \forall t \quad (4.4)$$

Equation 4.5 ensures the amount of cellulosic ethanol sold to the market cannot be more than the market demand at a given time period.

$$S_{m_e, t}^{\xi, tm} \leq d_{m_e, t}^{cm, \xi} \quad \forall m_e, \forall tm, \forall \xi, \forall t \quad (4.5)$$

Equation 4.6 ensures the amount of corn ethanol produced should be at least as much as the amount sold in any given time period.

$$z_{k_c, t}^{tm, \xi} \leq 0.45D_t \quad \forall k_c, \forall tm, \forall \xi, \forall t \quad (4.6)$$

Equation 4.7 ensures the amount of cellulosic ethanol produced should be at least as much as the amount sold in any given time period.

$$z_{k_m, t}^{tm, \xi} \geq 0.55D_t \quad \forall k_m, \forall tm, \forall \xi, \forall t \quad (4.7)$$

Equation 4.8 is the total production from corn and cellulosic demand should be equal to total demand

$$z_{k_c, t}^{tm, \xi} + z_{k_m, t}^{tm, \xi} \geq D_t \quad \forall k_m, \forall k_c, \forall tm, \forall \xi, \forall t \quad (4.8)$$

Equation 4.9 total production from corn and cellulosic demand should be equal to total demand

$$d_{c_e, t}^{tm, \xi} + d_{m_e, t}^{cm, \xi} = D_t \quad \forall c_e, \forall m_e, \forall tm, \forall \xi, \forall t \quad (4.9)$$

Equation 4.10 ensures the amount of corn ethanol produced should be always less than the ethanol plant production capacity.

$$z_{k_c, t}^{tm, \xi} \leq VCap_{k_c, t} \quad \forall k_c, \forall tm, \forall \xi, \forall t \quad (4.10)$$

Equation 4.11 ensures the amount of cellulosic ethanol produced should be always less than the cellulosic plant production capacity.

$$z_{k_m,t}^{tm,\xi} \leq VCap_{k_m,t} \quad \forall k_m, \forall tm, \forall \xi, \forall t \quad (4.11)$$

Fixed capacity constraints

Equation 4.12 is the capacity of corn based warehouse

$$Capf_{wco} \min \leq Xc_{c_f,t}^{k_c} \leq Capf_{wco} \max \quad \forall c_f, \forall k_c, \forall wco, \forall t \quad (4.12)$$

Equation 4.13 is the capacity of cellulosic based warehouse

$$Capf_{wce} \min \leq Xc_{m_f,t}^{k_m} \leq Capf_{wce} \max \quad \forall m_f, \forall k_m, \forall wce, \forall t \quad (4.13)$$

Equation 4.14 is the capacity of corn based biorefinery

$$Capf_{kco} \min Y_{c,q} \leq VCap_{k_c,t} \leq Capf_{kco} \max Y_{c,q} \quad \forall c, \forall q, \forall k_c, \forall kco, \forall t \quad (4.14)$$

Equation 4.15 is the capacity of cellulosic based biorefinery

$$Capf_{kce} \min Y_{c,q} \leq VCap_{k_m,t} \leq Capf_{kce} \max Y_{c,q} \quad \forall c, \forall q, \forall k_m, \forall kce, \forall t \quad (4.15)$$

Variable capacity constraints

Equation 4.16 is the variable capacity of corn based warehouse

$$Capv_{wco} \min \leq Xc_{c_f,t}^{k_c} \leq Capv_{wco} \max \quad \forall c_f, \forall k_c, \forall wco, \forall t \quad (4.16)$$

Equation 4.17 is the variable cost of cellulosic based warehouse

$$Capv_{wce} \min \leq Xc_{m_f,t}^{k_m} \leq Capv_{wce} \max \quad \forall m_f, \forall k_m, \forall wce, \forall t \quad (4.17)$$

Equation 4.18 is variable cost of the capacity of corn based biorefinery

$$Capv_{kco} \min Y_{c,q} \leq VCap_{k_c,t} \leq Capv_{kco} \max Y_{c,q} \quad \forall c, \forall q, \forall k_c, \forall kco, \forall t \quad (4.18)$$

Equation 4.19 is the variable capacity of cellulosic based biorefinery

$$Capv_{kce} \min Y_{c,q} \leq VCap_{k_m,t} \leq Capv_{kce} \max Y_{c,q} \quad \forall c, \forall q, \forall k_m, \forall kce, \forall t \quad (4.19)$$

Feedstock conversion constraints

Equation 4.20 ensures the amount of corn ethanol produced is proportional to the rate of conversion of the feedstock.

$$z_{k_c,t}^{tm,\xi} = \beta(Xp_{c_f,t}^{w_c,\xi}) \forall k_c, \forall w_c, \forall \xi, \forall c_f, \forall tm, \forall t \quad (4.20)$$

Equation 4.21 ensures the amount of cellulosic ethanol produced is proportional to the rate of conversion in the products production.

$$z_{k_m,t}^{tm,\xi} = \lambda(Xp_{m_f,t}^{w_m,\xi}) \forall k_m, \forall w_m, \forall \xi, \forall m_f, \forall tm, \forall t \quad (4.21)$$

Equation 4.22 ensures the amount of corn feedstock pretreated and transported to corn biorefinery plants is less or equal to the plant capacity.

$$\sum_{w_c \in W_C} Xp_{c_f,t}^{w_c,\xi} \leq VCap_{k_c,t} \forall k_m, \forall w_c, \forall \xi, \forall m_f, \forall t \quad (4.22)$$

Equation 4.23 ensures the amount of cellulosic feedstock pretreated transported to biorefinery plants is less or equal to the plant capacity.

$$\sum_{w_m \in W_M} Xp_{m_f,t}^{w_m,\xi} \leq VCap_{k_f,t} \forall k_m, \forall w_m, \forall \xi, \forall m_f, \forall t \quad (4.23)$$

End-product constraints

Equation 4.24 ensures the amount of lignin produced is proportional to the rate of consumption of the cellulosic feedstock.

$$\partial_{fl}(Xp_{m_f,t}^{w_m,\xi}) = CL_{m_e,t}^{k_m,\xi} \forall k_m, \forall m_e, \forall w_m, \forall \xi, \forall m_f, \forall t \quad (4.24)$$

Equation 4.25 ensures the amount of protein produced is proportional to the rate of consumption of the cellulosic feedstock.

$$\partial_{fp}(Xp_{m_f,t}^{w_m,\xi}) = CP_{m_e,t}^{k_m,\xi} \forall k_m, \forall m_e, \forall w_m, \forall \xi, \forall m_f, \forall t \quad (4.25)$$

Equation 4.26 ensures the amount of DDGS produced is proportional to the rate of consumption of the corn feedstock.

$$\nabla_{cd}(Xp_{c_f,t}^{w_c,\xi})=CD_{c,t}^{k_m,\xi}\forall k_m,\forall m_e,\forall w_c,\forall \xi,\forall c_f,\forall t \quad (4.26)$$

Equation 4.27 ensures the amount of corn oil produced is proportional to the rate of consumption of the corn feedstock.

$$\nabla_{cco}(Xp_{c_f,t}^{w_c,\xi})=CO_{c,t}^{k_m,\xi}\forall k_m,\forall m_e,\forall w_c,\forall \xi,\forall c_f,\forall t \quad (4.27)$$

4.4.2. Mathematical model with hedging strategy

This section proposes a mathematical model with hedging strategy. Again, the assumption here is that the decision variables such as the amount of corn feedstock purchased, and the amount of ethanol sold are decided through taking a futures position in the market. Therefore, equation 4.2 is replaced by equation 4.a1 which is the revenue obtained by selling corn ethanol c_e produced at plant k_c and sold at the trade market tm for time period t during hedging. The rest of the equations are as follows:

Rch is the hedging revenue in selling corn ethanol c_e at the trade market cm for time period t

$$Rch = \sum_{k_c \in KC} \sum_{tm \in TM} \sum_{t \in T} Pz_{c_e,tm}^{F,t} HZ_{c,tm}^{F,t} \quad (4.a1)$$

Rceh is the hedging revenue in selling cellulosic ethanol m_e at the trade market cm for time period t

$$Rceh = \sum_{k_m \in KM} \sum_{c_m \in CM} \sum_{t \in T} Pz_{m_e,tm}^{F,t} HZ_{m,tm}^{F,t} \quad (4.a2)$$

We assume the revenue for lignin, protein, DDGS, and corn oil are same since there is no liquidity for their markets: the same equations are shown below:

Rddgh is the hedging revenue obtained by selling corn DDGS produced at plant k_c sold to cash market cm for time period t

$$Rddgh = E_{\xi} \left(\sum_{k_c \in KC} \sum_{tm \in TM} \sum_{t \in T} Pcd_{c_e, t}^{\xi, tm} CD_{c, t}^{k_c, \xi} \right) \quad (4.a3)$$

Rcoh is the hedging revenue obtained by selling corn oil produced at plant k_m and sold to market cm at time period t

$$Rcoh = E_{\xi} \left(\sum_{k_c \in KC} \sum_{tm \in TM} \sum_{t \in T} Pco_{c_e, t}^{\xi, tm} CO_{c, t}^{k_c, \xi} \right) \quad (4.a4)$$

Rlh is the hedging revenue obtained by selling lignin produced and sold on the cash market cm for time period t

$$Rlh = E_{\xi} \left(\sum_{k_m \in KM} \sum_{tm \in TM} \sum_{t \in T} Pl_{m_e, t}^{\xi, tm} CL_{m, t}^{k_m, \xi} \right) \quad (4.a5)$$

Rph is the hedging revenue obtained by selling protein produced sold to the trade market cm at time period t

$$Rph = E_{\xi} \left(\sum_{k_c \in KC} \sum_{tm \in TM} \sum_{t \in T} Pp_{m_e, t}^{\xi, tm} CP_{m, t}^{k_m, \xi} \right) \quad (4.a6)$$

The rest of the constraints are all applicable for the hedging case

Costs: hedging for corn and cellulosic

HCp is the total corn feedstock purchased cost from source i_c to warehouse w_c

$$HCp = \sum_{w_c \in WC} \sum_{t \in T} PX_{c_f, tm}^{F, t} X_{c_f, tm}^{F, t} + cpo X_{c_f, tm}^{F, t} \quad (4.a7)$$

Hce is the cost of corn ethanol from biorefinery k_c to market tm in time period t

$$Hce = \sum_{k_c \in KC} \sum_{c_m \in CM} \sum_{t \in T} T_{c_e, t}^{k_c, cm} dc_{c_e, t}^{k_c, tm} HZ_{c_e, tm}^{F, t} \quad (4.a8)$$

Hcel is the total cost of cellulosic feedstock that are purchased from supply source

$$Hcel = \sum_{w_m \in WM} \sum_{t \in T} PX_{m_f, cm}^{S,t} X_{m_f, cm}^{S,t} \quad (4.a9)$$

HCcel is the cost of cellulosic ethanol from biorefinery k to demand zones or trade market i

$$HCcel = \sum_{k_m \in KM} \sum_{t \in T} T_{m_e, t}^{k_m, cm} dc_{m_e, t}^{k_m, cm} HZ_{m_e, cm}^{F,t} \quad (4.a10)$$

Subject to: Constraints: hedging for corn and cellulosic

Warehouse capacity constraints

Equation 4.28 ensures the corn feedstock supplied from the source to the warehouse should be less than or equal to the amount available at the source

$$\sum_{i_c \in IC} X_{c_f, m}^{F,t} \leq Xp_{c_f, t}^{w_c, \xi} \quad \forall c_f, \forall F, \forall w_c, \forall \xi, \forall tm, \forall t \quad (4.28)$$

Equation 4.29 ensures the cellulosic feedstock supplied from the source to the warehouse should be less than or equal to the amount available at the source

$$\sum_{i_m \in IM} X_{m_f, cm}^{S,t} \leq Xp_{m_f, t}^{w_m, \xi} \quad \forall m_f, \forall S, \forall w_m, \forall \xi, \forall cm, \forall t \quad (4.29)$$

Demand, sales, capacity and production constraints

Equation 4.30 ensures the amount of corn ethanol sold to each trade market cannot be more than the market demand at a given time period.

$$S_{c_e, t}^{\xi, tm} \leq d_{c_e, t}^{tm} \quad \forall c_e, \forall tm, \forall \xi, \forall t \quad (4.30)$$

Equation 4.31 ensures the amount of cellulosic ethanol sold to the market cannot be more than the market demand at a given time period.

$$S_{m_e, t}^{\xi, cm} \leq d_{m_e, t}^{cm} \quad \forall m_e, \forall tm, \forall \xi, \forall t \quad (4.31)$$

Equation 4.32 ensures the corn ethanol produced should be at least as much as the amount sold in any given time period.

$$HZ_{c_e,tm}^{F,t} \leq 0.45D_t \forall c_e, \forall tm, \forall F, \forall t \quad (4.32)$$

Equation 4.33 ensures the cellulosic ethanol produced should be at least as much as the amount sold in any given time period.

$$HZ_{m_e,cm}^{F,t} \geq 0.55D_t \forall m_e, \forall cm, \forall F, \forall t \quad (4.33)$$

Fixed cost for warehouse and biorefinery

Equation 4.34 ensures the corn ethanol produced should be always less than the ethanol plant production capacity.

$$HZ_{c_e,tm}^{F,t} \leq Cap_{k_c,t} \forall c_e, \forall tm, \forall F, \forall k_c, \forall t \quad (4.34)$$

Equation 4.35 ensures the cellulosic ethanol produced should be always less than the cellulosic plant production capacity.

$$HZ_{m_e,cm}^{F,t} \leq Cap_{k_m,t} \forall m_e, \forall cm, \forall F, \forall k_m, \forall t \quad (4.35)$$

Equation 4.36 is the total production from both corn and cellulosic demand should be equal to total demand

$$HZ_{m_e,cm}^{F,t} + HZ_{c_e,tm}^{F,t} \geq D_t \forall m_e, \forall tm, \forall F, \forall c_e, \forall t \quad (4.36)$$

Equation 4.37 total production from corn and cellulosic demand should be equal to total demand

$$d_{c_e,t}^{tm} + d_{m_e,t}^{cm} = D_t \forall c_e, \forall tm, \forall cm, \forall m_e, \forall t \quad (4.37)$$

Fixed cost for warehouse and plant

Equation 4.12 – 4.15 are repeated for the fixed cost of warehouse and biorefinery

Variable cost for warehouse and plant

Equation 4.16 – 4.19 are also repeated for the variable cost of warehouse and biorefinery

Feedstock conversion constraints

Equation 4.38 ensures the amount of corn ethanol produced is proportional to the rate of conversion of the feedstock.

$$HZ_{c_e,tm}^{F,t} = \beta(XP_{c_f,t}^{w_c,\xi}) \forall c_e, \forall tm, \forall F, \forall w_c, \forall c_f, \forall \xi, \forall t \quad (4.38)$$

Equation 4.39 ensures the amount of cellulosic ethanol produced is proportional to the rate of conversion in the products production.

$$HZ_{m_e,cm}^{F,t} = \lambda(XP_{m_f,t}^{w_m,\xi}) \forall m_e, \forall cm, \forall F, \forall w_m, \forall m_f, \forall \xi, \forall t \quad (4.39)$$

Hedging constraints

Equation 4.40 is the decision to buy corn, which is based on the futures amount and price

$$X_{c_f,tm}^{F,t} \leq MY_{corn_fut}(\xi) \forall F, \forall tm, \forall c_f, \forall \xi, \forall t \quad (4.40)$$

Equation 4.41 is the decision to buy corn, which is based on the spot amount and price

$$X_{c_f,tm}^{F,t} \leq MY_{corn_spot}(\xi) \forall F, \forall tm, \forall c_f, \forall \xi, \forall t \quad (4.41)$$

Equation 4.42 is the binary decision to buy either corn or cellulosic, which is stochastic

$$Y_{corn_spot}(\xi) + Y_{corn_fut}(\xi) = 1 \quad \forall \xi \quad (4.42)$$

Equation 4.43 is the binary decision to buy either cellulosic, which is based on spot

$$Y_{cell_spot}(\xi) + Y_{cell_fut}(\xi) = 1, \text{ but } Y_{cell_fut}(\xi) = 0 \quad \forall \xi \quad (4.43)$$

Equation 4.44 is the decision to buy cellulosic, which is based on the spot amount and price

$$X_{m_f,cm}^{S,t} \leq MY_{cell_spot}(\xi) \forall S, \forall cm, \forall m_f, \forall \xi, \forall t \quad (4.44)$$

Equation 4.45 is the decision to buy corn and cellulosic feedstock being equal to feedstock

$$X = X_{m_f, cm}^{S,t} + X_{c_f, tm}^{F,t} \quad \forall S, \forall cm, \forall F, \forall c_f, \forall m_f, \forall t \quad (4.45)$$

Equation 4.46 is the decision to buy corn, which is based on the futures amount and price

$$SX_{c_f, tm}^{F,t} - \alpha * Avg(PX_{c_f, tm}^{F,t}) \leq Y_{corn_fut}(\xi) \quad \forall F, \forall tm, \forall c_f, \forall \xi, \forall t \quad (4.46)$$

Equation 4.47 is the decision to buy corn, which is based on the spot amount and price

$$\alpha * Avg(PX_{c_f, tm}^{F,t}) - SX_{c_f, tm}^{F,t} \leq Y_{corn_spot}(\xi) \quad \forall F, \forall tm, \forall c_f, \forall \xi, \forall t \quad (4.47)$$

4.5. Solution Technique: Multi-cut Benders decomposition

Multi-cut Benders decomposition (MBD) is applied to solve both the hedging and non-hedging models. The MBD algorithm is to add one cut per realization of uncertainty to the master problem in each iteration. This essentially means to add Benders cuts as the number of scenarios added to the master problem in each iteration (You and Grossmann, 2011). Some advantages in using the MBD algorithm is the improved percentage in the bounds. This method is an extension of the Benders decomposition algorithm as discussed in Kalvelegen (2002). In order not to have redundancy in equations, a general two-stage stochastic problem is introduced below to make reference to the algorithm easy and for clearer explanation. The two-stage stochastic problem for the MBD algorithm is discussed further. Equation 4.48 is the general two-stage stochastic problem, while, equation 4.49 and 4.50 are the master and sub-problems respectively.

Two-stage stochastic problem

$$\begin{aligned} \text{Max} \quad & z = c^T x + E_\zeta [\max q(w)^T y(w)] \\ \text{s.t.} \quad & Ax \leq b, \\ & T(w)x + Wy(w) = h(w) \\ & x \geq 0, y(w) \geq 0. \end{aligned} \quad (4.48)$$

Master problem

$$\begin{aligned}
\text{Min } z_1 &= c^T x + \sum_{\xi} p_{\xi} \eta_{\xi} \\
\text{s.t. } Ax &= b, \\
\eta_{\xi} &\geq \pi_{\xi} (h_{\xi} x + T_{\xi}) \quad \forall \xi \in \xi \\
x &\geq 0, z_{j,k} \geq 0.
\end{aligned} \tag{4.49}$$

Sub problem

$$\begin{aligned}
\text{Min } z_2 &= d_{\xi}^T y_{\xi}(\xi) \\
\text{s.t. } W_{\xi} y_{\xi}(\xi) &= h_{\xi}(\xi) - T_{\xi} xbar \\
x &\geq 0, y(\xi) \geq 0
\end{aligned} \tag{4.50}$$

Where $xbar$ is the optimal solution of x in the first stage

The Multi-cut Benders algorithm is as follows and it is shown in Figure 12:

Step 1. Set $l=1$, $\varepsilon, UB=+\infty, LB=-\infty$, where l is the iteration counter, and $UB_l=\infty$, that is, upper bound is set to positive infinity, and the lower bound is set to negative infinity, $LB_l=-\infty$

Step 2. Generate the scenarios for N samples for the demand and price data. Solve equation 4.49 and add $\eta_{\xi} \geq \pi_{\xi} (h_{\xi} x + T_{\xi})$ which is like a ‘hot’ start to reach optimality

Step 3. Solve the sub problem, i.e. equation 4.50 to obtain the optimal first-stage decisions, i.e. $xbar$

Step 4. Determine the dual of the sub problem, and represent them by the dual variables, in this case: π_{ξ}

Step 5. Update the upper bound by setting: $UB_{l+1} = \min\{UB_l, z_1 + z_2\}$, where z_1 and z_2 are the objective function value of the master and sub problems respectively

Step 6. Update the lower bound problem by using: $LB_{l+1} = z_1 + \eta$, where z_1 is the master problem objective function with cut, η

Step 7. Add cut to the master problem

Step 8. Proceed to test for the optimal solution with a stopping criteria, otherwise, set the iteration counter to $l=l+1$. The criterion uses a tolerance which is a pre-determined for the stopping criterion

Step 9. Solve the updated master problem and add the probabilities and scenarios to the cut and go back to step 3

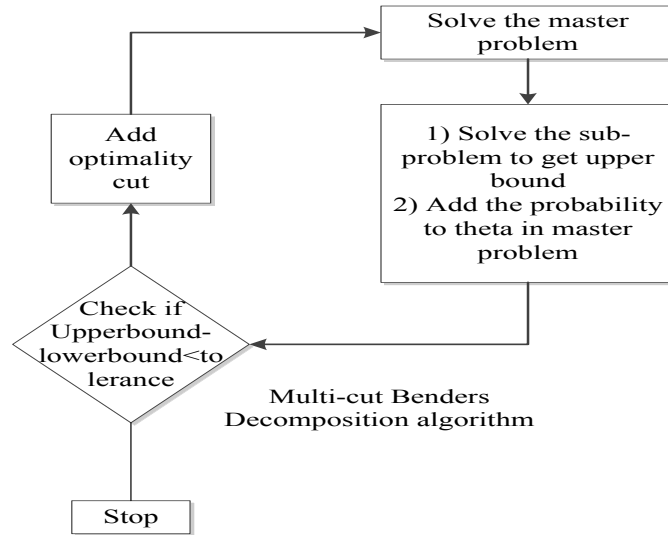


Figure 12. Flow chart of the regular Multi-cut Benders decomposition

4.6. Case study

The case study will examine a hybrid generation based biofuel supply chain (HGBSC) in the U.S. state of North Dakota (ND). ND has already established corn ethanol biorefinery plants because of the vast nature and availability of corn feedstock (Berdahl et al., 2005; Schmer, Vogel, Mitchell, and Perrin, 2008). Studies such as Zhang, Osmani, Awudu, and Gonela (2012) have also evaluated cellulosic biofuel potential as a biomass energy crop in the Northern Great Plains (NGP) of the United States. The study concludes that the environmental and soil conditions in the NGP are suitable for the commercial cultivation of cellulosic feedstock such as switchgrass. So the raw materials for the end-products are well established. The case study will focus on the combinations of these two raw materials to serve as feedstock sources to form an ethanol supply chain that will be able to meet the ND mandate for advance ethanol consumption in 2022 by the

REA.

Raw materials are purchased from immediate supply sources. Feedstocks are pre-treated at the warehouse, and the pre-treated raw materials transported to the production facility. Four different biofuel refinery facilities convert the raw materials into end-products, two producing corn-based ethanol, and the other two plants for cellulosic-based ethanol. The entire 53 counties in North Dakota are considered as the demand zones.

First analysis is conducted on the historical data of corn and ethanol price and it was found that corn feedstock prices are more volatile as compared to ethanol. The heuristic method which considers buying corn futures when the price of corn at the spot price is assumed to be greater than 5% of the futures price is considered. This means a method of buying corn feedstock using the spot price is exercised if futures price is greater than the 1.05 times the mean of the sample price generated. A heuristic method is subsequently used for the hedging. Therefore, a multi-period consisting of quarterly time horizon is used.

The study considers hedging and non-hedging scenarios for buying and selling feedstock and end-products respectively. Hedging uses futures price which is generated by mean reversion as discussed earlier. Non-hedging generates similar price scenarios using mean reversion but in this case from a different sample. This assumption is used to ensure fairness and also to reflect the real case on the market.

In this research, corn and cellulosic based ethanol are sold to the commodity market using futures, while the feedstock for corn is bought using futures, and cellulosic is purchased at the spot price. This is being implemented as a research direction for the paper published by (Awudu and Zhang, 2012). The representative supply chain case study is shown in Figure 13.

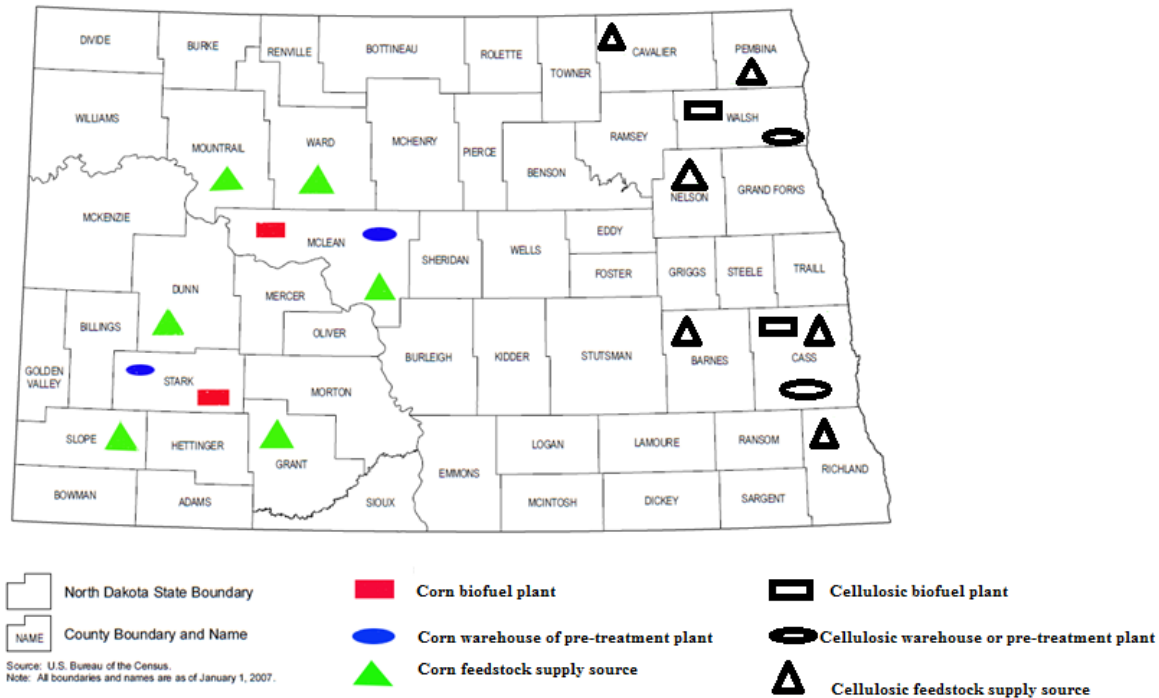


Figure 13. North Dakota Map with counties for case study

4.6.1. Hedging strategies

As discussed in section 1, hedging strategy is a mechanism commonly used to reduce extreme risk due to price volatilities of commodities or stocks (Manuj and Mentzer, 2008). The concept of futures gives additional flexibility in trading with commodities to buy or sell a futures contract at a designated strike price (Feder, Just, and Schmitz, 1980). Futures hedging strategy is proposed in this model for a quarterly-period financial hedging strategy used for hedging against the uncertain corn feedstock and corn ethanol prices. Similar planning approach is used for the cellulosic feedstock and ethanol, but the cellulosic feedstock uses a spot price for the decision making while cellulosic ethanol uses futures.

4.6.2. Hedging and non-hedging diagrams

The hedging diagrams for the traditional and proposed hedging strategies are shown in Figures 14 and 15. Figure 14 represents the typical traditional case where no hedging position is taken, and figure 15 and is the proposed hedging strategy. Time periods $t-m$, t , and $t+m$ represent previous, current, and future times respectively. In the first hedging diagram, both corn and cellulosic feedstocks are purchased based on a spot price and no hedging approach is adopted. The second diagram represents the proposed hedging strategy where the corn is hedged in time $t-m$ and the purchase is executed at time t . The sale of ethanol and other by-products are executed at time periods $t+m$, after an appropriate hedge position is taken at time t . Production of ethanol takes place between t and $t+m$. Ethanol production takes place between t and $t+m$.

The non-hedging, hedging, and heuristic methods are shown in Figures 14-16.

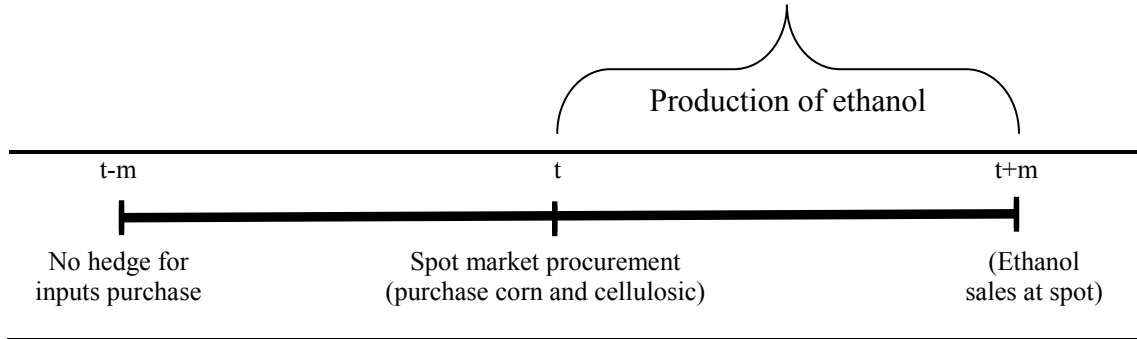


Figure 14. Non-hedging method

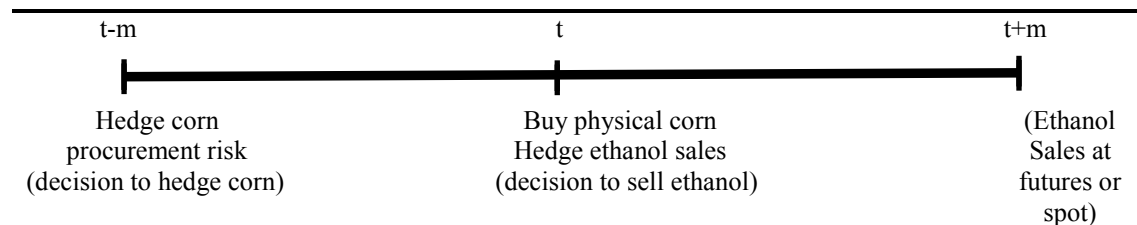


Figure 15. Hedging method

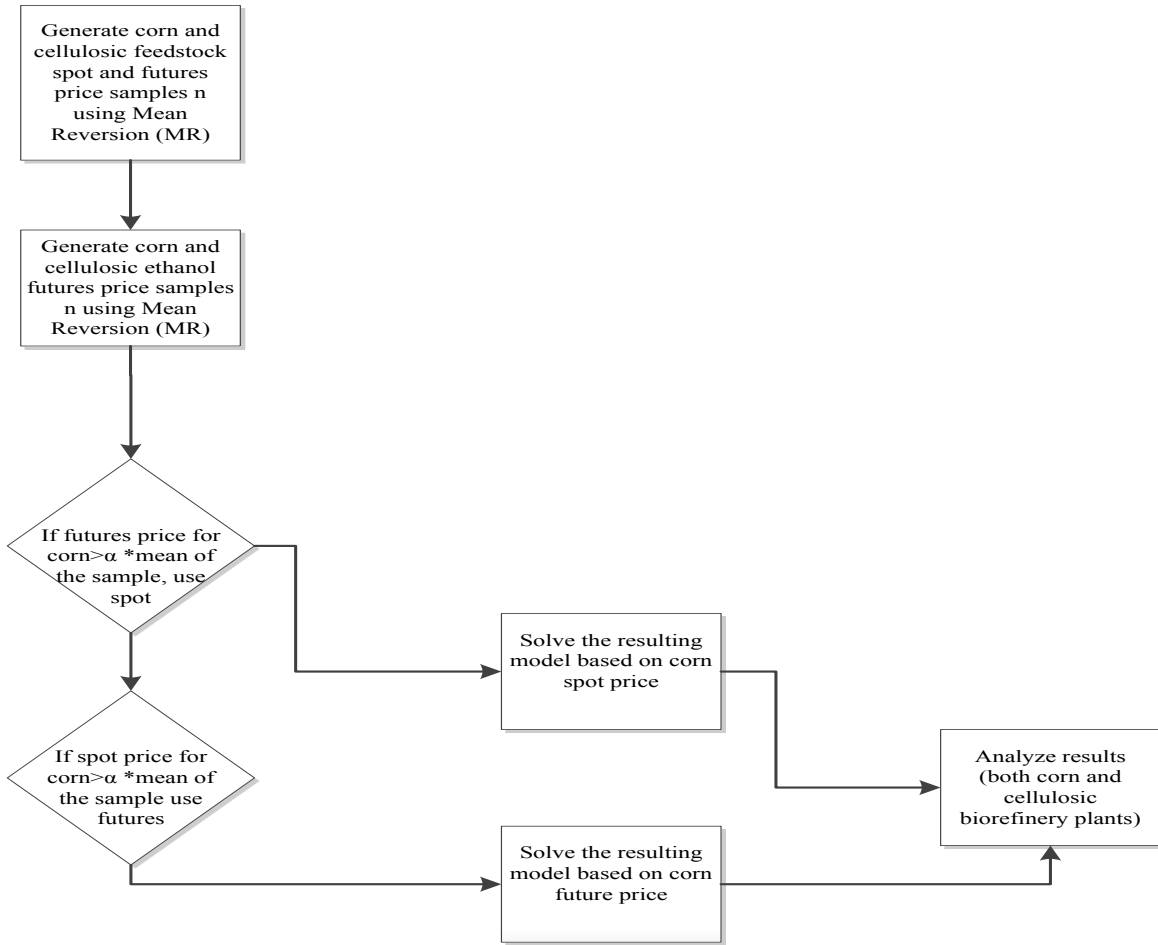


Figure 16. Hedging strategy diagram

4.7. Modeling price uncertainty

Mean reversion (MR) models are widely used in finance. In this dissertation, mean reversion is used to model the price uncertainties of ethanol and corn feedstock. Mean reversion models are important since they reflect the proper or accepted mechanisms with which the stock market or commodity prices behave (Sørensen, 2002). The concept is that the high and low prices of a commodity or stock are temporary, and that the stock price will move or shift to the average price over time (Schwartz, 1997). They are widely used to model interest rates, especially for commodities. Another popular name of this model is the Ornstein and Uhlenbeck or ‘O-U’ process. This is also used for modeling price uncertainties as in Dias and Rocha (1999).

The Ornstein Uhlenbeck process is widely used for modeling a mean reverting process which is given by the formula below:

$$ds = \lambda(\mu - S)dt + \sigma dW_t \quad (\text{iii})$$

Where W_t is the Brownian Motion, with $dW_t \sim N(0, \sqrt{dt})$, λ is the speed of mean reversion, μ is the long run mean which the process tends to revert to, and σ the measure of the process volatility. Where dt is the change in time (Postali and Picchetti, 2006). This section of the dissertation adopts this model by first of determining the mean value of the data provided and using it to calibrate the required parameters.

4.7.1. Calibrating the price (MR) parameters

The reversion rate and mean level can be calculated from the coefficients of a linear fit between the log prices and their first difference scaled by the time interval parameter. The equations are provided below: Equation iii can be re-written as $S_t - S_{t-1} = \lambda(\mu - S)\Delta t + \sigma dW_t \dots$

(iv) according to Poterba and Summers (1988). Separating terms and expressing the equation in a linear regression form $y = a + bx + \varepsilon_t \dots$ (v) and after mathematical manipulation yields the

following terms for the reversion rate and mean level respectively: $\lambda = \frac{\ln(b)}{\Delta t} \dots$ (vi) and

$$\mu = \frac{a}{1-b} \quad (\text{vii})$$

4.7.2. Proposed heuristic hedging strategy

The heuristic method is used to provide a computationally tractable approach to solve the problem. A generalized heuristic method uses the mean reversion model to generate n sample data for both the corn spot and futures prices as discussed in the problem statement. Following

the discussion on hedging, the next section introduces the modeling of price uncertainties. A sample of the scenario generated in the heuristic method is shown in Table 13.

Table 13. Sample heuristic strategy

Scenario	Spot_corn	Future_corn	Mean	Y_spot	Y_fut	PRICE
1	7.459788464	7.041125708	7.3512	0	1	7.0411257
2	6.857595768	6.845238288	7.3512	0	1	6.8452383
3	7.406766642	7.387176137	7.3512	1	0	7.4067664
4	7.416234608	7.205385202	7.3512	0	1	7.2053852
5	7.096484325	6.919995895	7.3512	0	1	6.9199959
6	7.397894038	7.406470446	7.3512	1	0	7.397894
7	7.3517407	6.812084249	7.3512	0	1	6.8120842
8	6.991755743	7.446363526	7.3512	1	0	6.9917557
9	6.812084249	6.7840901	7.3512	0	1	6.7840901
10	6.996535871	6.982476173	7.3512	0	1	6.9824762

4.7.3. Input parameters

The following input parameters are provided in Tables 14 and 15. Values of other key input parameters are referenced from Zhang et al. (2012). Mean reversion is used for the price uncertainty modeling. Corn and cellulosic feedstock prices are generated for the generalized number of scenarios used in the study. Similar analysis is conducted for the ethanol. Both corn and cellulosic ethanol are also generated using the mean reversion prices. Non-hedging uses the spot price for the decision making while hedging for both feedstock and end-products is based on the heuristic method developed.

The detailed heuristic method purchases cellulosic feedstock at a spot price. The heuristic method uses the mean reversion model to generate sample data for both the corn spot and futures prices. Similarly, corn and cellulosic ethanol analysis are conducted using the method discussed. A method of buying corn feedstock using the spot price is used if futures price is greater than the 1.05 times the mean of the sample price generated. Meanwhile, similar heuristic

method is adopted for the futures. It should be noted that the 5% threshold used for the analysis is to conform to the value at risk, which is 5% of the downside risk. Input data for the corn and cellulosic biorefinery are shown in Tables 14 and 15.

Table 14. Corn BSC and input data

Parameters	Values	Units
		\$
Cost of corn feedstock	MR (6.75,0.095)	(dollars)/bushel
Price of corn ethanol	MR (2.75,0.095)	\$ (dollars)/gal
Corn ethanol demand	Based on county/month	gallons
Capacity of corn biorefinery plant 1	120,000,000	Gallons/yr
Capacity of corn biorefinery plant 2	120,000,000	Gallons/yr
Unit raw material transportation cost to plants	0.0718/mile	\$ (dollars)
Unit end-products transportation cost	0.0718/mile	\$ (dollars)
Unit inventory holding cost for raw material	0.005	\$ (dollars)
Unit inventory holding cost for end-product	0.005	\$ (dollars)
Unit penalty cost for unmet demand	0.000285	\$ (dollars)
Unit cost per processing	1.24/bushel	\$ (dollars)

Cost categories ranging from energy, chemical, and processing costs are added. Example of these cost factors are enzymes, boiling and heating, licence, maintenance, depreciation, boiling, denaturing, natural gas, electricity, propane operation, etc are quantified based on the biorefinery plants capacity and incorporated in our model.

Table 15. Cellulosic BSC and input data

Parameters	Values	Units
Cost of cellulosic feedstock	MR (3.8,0.095)	\$ (dollars)/ton
Price of cellulosic ethanol	MR (2.75,0.095)	\$ (dollars)/gal
Cellulosic ethanol demand	Based on county/month	gallons
Capacity of cellulosic biorefinery plant 1	120,000,000	Gallons/yr
Capacity of cellulosic biorefinery plant 2	120,000,000	Gallons/yr
Unit raw material transportation cost to plants	0.158/mile	\$ (dollars)
Unit end-products transportation cost	0.158/mile	\$ (dollars)
Unit inventory holding cost for feedstock	0.0155	\$ (dollars)
Unit inventory holding cost for ethanol	0.15	\$ (dollars)
Unit penalty cost for unmet demand	0.005	\$ (dollars)
Unit cost per processing	1.24/ton	\$ (dollars)

4.8. Results and analysis

The models are solved by the commercial GAMS 26.3.5 version using a CPLEX solver. A Sony Viao of Intel 1.6 Centrino processor of 2.5GHz is used. The results and subsequent sensitive analyses are presented in the next section.

4.8.1. Results summary

The results summary is shown in Table 16. Mean profits represent the entire expected profit realization for the scenarios adopted. The variance and standard deviation for these scenarios are also calculated. The respective hedging diagrams are shown.

Table 16. Results summary of profit

Model	Mean	Variance	STD
Hedging	1.321E+08	0.832E+5	912.2456661
Non-hedging	1.283E+08	1.379E+6	1186.776531

4.8.2. Risk analyses with and without hedging

The analyses in Figure 17 show the profit and risk curves for hedging and non-hedging. From the results, non-hedging profits are low for higher probabilities or risks as compared to hedging. This means hedging gives better profit realizations at low risks compared to non-hedging. A typical example is the hedged profit margin of \$1.255E8. This value has a risk of approximately 0.25 for non-hedging as compared to a risk of 0.00 for hedging. The opposite holds for higher values. The non-hedged profit has a risk factor of approximately 0.99 for a profit value of \$1.386E8, as compared to the hedged case which has the same profit for a risk of 0.99 or approximately 1. This analysis is in line with the literature which concludes that hedging advantages are realized at low profit values as compared to high profit values. In this instance the decision maker will be circumspect in taking a hedge position or not for a particular profit realization. Furthermore, at a profit of \$1.385E8, the risks of hedging and non-hedging are the

same. This means irrespective of the position taken, the ethanol producer will make that amount of profit, meaning it is better not to hedge since hedging might incur some cost, especially if say futures is being used. Figure 17 further provides some managerial insights that are concluded in this analysis. That is hedging is a mechanism that can reduce the exposure to risk, but does not mean higher profits will be realized anytime hedging is used. The conclusion that can be drawn from this chapter is that, hedging is good for smaller profits, but not necessarily larger profits, since compensation will be paid in terms of higher variance at higher profit values.

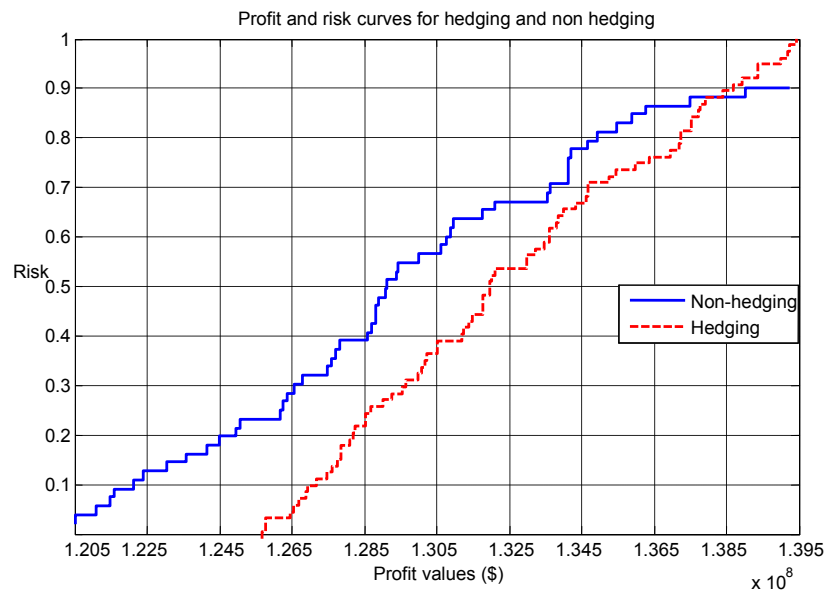


Figure 17. Risk curves comparison for profit with and without hedging

4.8.3. The impact of ethanol price on profit

Sensitivity analyses are conducted to analyze the results for the profit effect on certain parameter changes. The x-axis represents ethanol price and demand scenarios, while the y-axis represents expected profit. First, we study three separate scenarios by performing sensitivity analysis on how ethanol price and demand changes can affect the final profit realization when there are changes in these parameters. Scenario 3 is the base case. Scenarios 0, 1 and 2 are 15%,

10%, and 5% decrement in ethanol price and demand respectively. Scenarios 4, 5, and 6 are on the hand are 5%, 10%, and 15% increment in ethanol price and demand.

From Figure 18, it is clear that an increase in the price of end-products results in a significant change in the profit realization. An upward shift in price corresponds to an adjustable upward increase in profit. In the case of the non-hedging, the base profit increases by 2% percent when there is 5% increase in price.

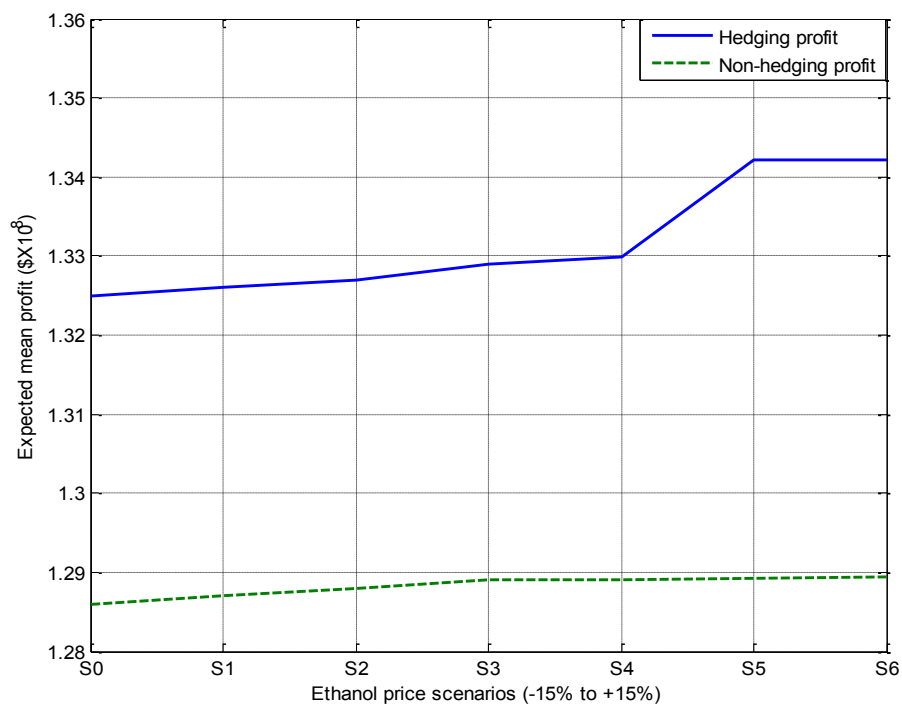


Figure 18. Profit graph with and without hedging for price changes

A profit increase of 2.67%, 2.69% are realized when the corresponding price changes are increased by 10% and 15% respectively. Similar analyses are conducted for the non-hedging in the demand changes and profit changes of 0.89%, 2.63%, and 2.68% are realized. This indicates that the expected profit is more sensitive to ethanol price than ethanol demand. Similar analyses can be conducted for the decrement in percentages which provide same profit percentages on the

down side are considered. Additional analyses can be conducted using Figure 19 as shown. Some managerial insight that can be given is that price changes has the highest impact in terms of changes, followed by demand.

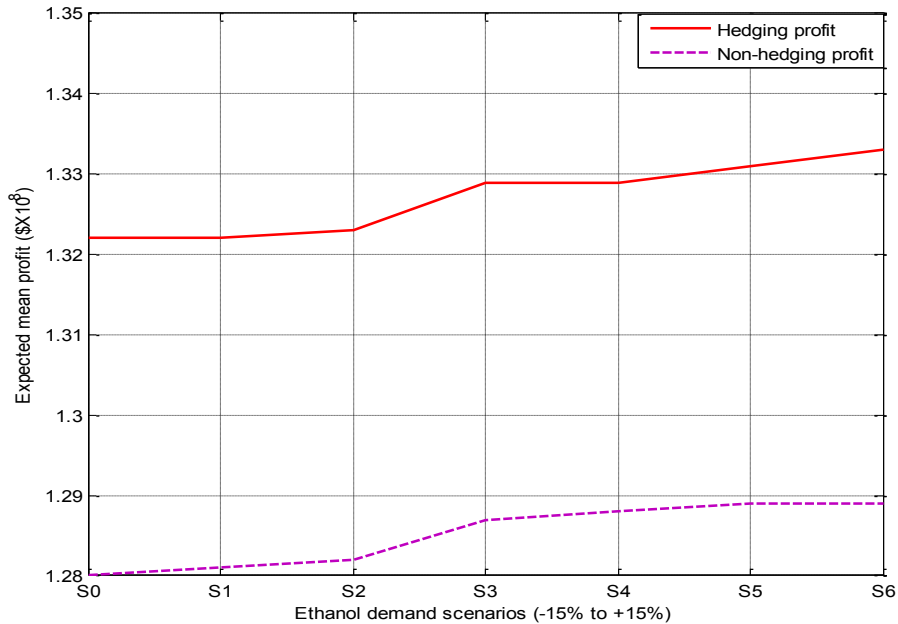


Figure 19. Profit graph with and without hedging for demand changes

4.8.4. The impact of raw materials cost on profit

Since there are two main types of biomass feedstock involved, further analyses are conducted to determine the impact of raw materials cost changes on the profit margin in the supply chain. Currently, the cost of biomass for cellulosic is cheaper as compared to corn feedstock. From the analyses performed, long term cost of biomass from cellulosic will be beneficial only if there are no changes in technology for ethanol production, pre-treatment plants, and other factors. From the bar charts, an approximate increase in the cost of corn will impact the profit more than that of cellulosic. One of the reasons that can be attributed to this is the fact that corn is traded as a commodity and has several impactors that could affect its price such as economic, political, and weather. Figure 20 therefore represents the profit distribution when the

costs of the cellulosic and corn feedstocks are decreased by 15% in both the hedging and non-hedging scenarios. It is observed that there is an approximately 1.37% and 3.97% increase for non-hedging and hedging profits respectively when these changes are made. Similar analyses can be conducted for increment in raw material cost and the results are shown in Figure 20.

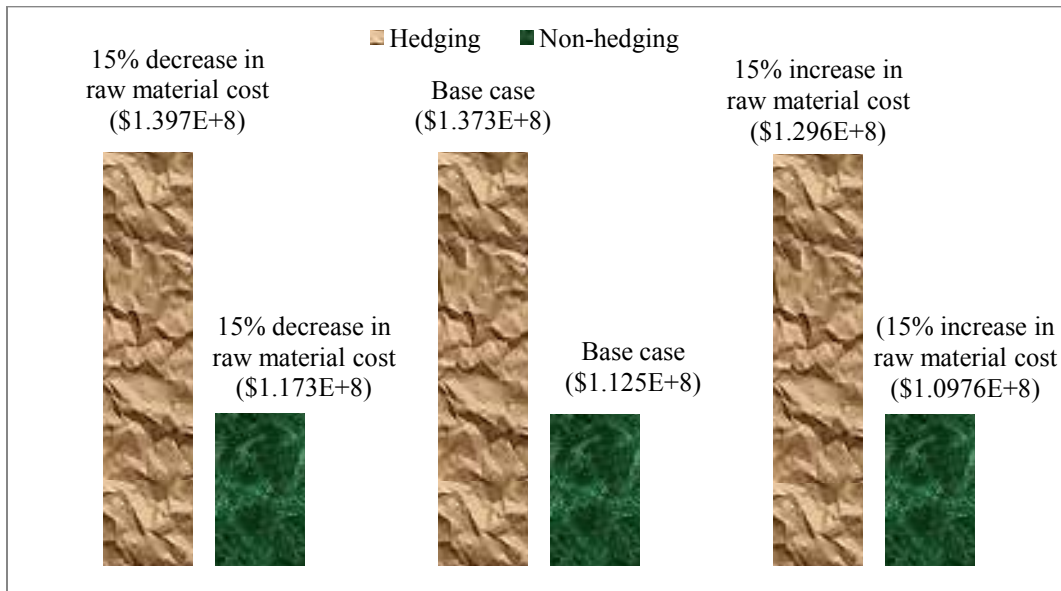


Figure 20. Graph comparison for feedstock changes in non-hedging

4.8.5. Profit contributions from all products

This analysis looks at the various contributions of the output products in making up the profit. Two main products are identified as the end-output, which are cellulosic and corn ethanol. There are four by-products, namely lignin and protein (grass left over) from cellulosic feedstock and corn oil and DDGS from corn respectively. The analyses are shown in Figures 21 and 22. The profit analyses are discussed as follows:

- 1) Hedging: The highest contribution is from corn and cellulosic ethanol which is 95.36%, followed by the by-products, which contribute about 4.64%. Ethanol is basically the mainly used product, followed by the by-products after production of the corn and

cellulosic ethanol, which can be used for animal feed such as DDGS and for energy production, such as lignin.

- 2) Non-hedging: Similarly, another analysis is conducted for the case with other analyses for the corn and cellulosic case without hedging. The highest contribution is from corn and cellulosic ethanol which is 96.57%, and then the by-products, which contribute about 3.44%.

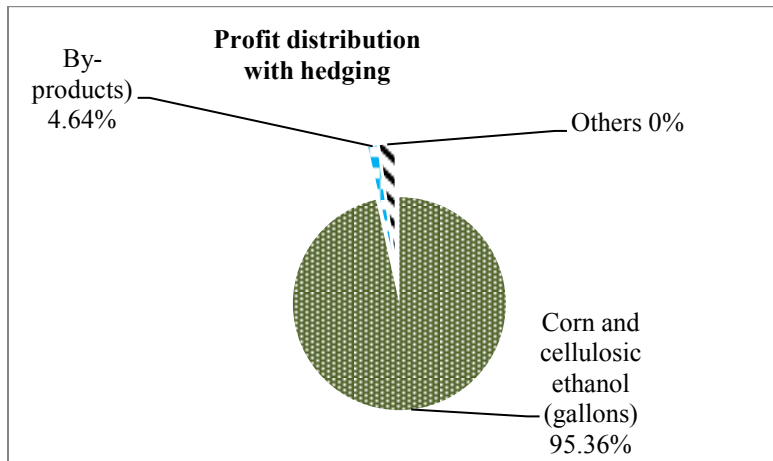


Figure 21. Profit contribution with hedging

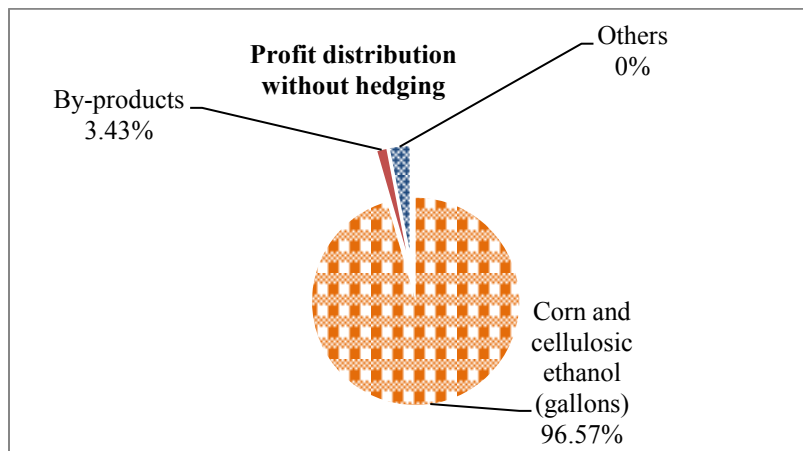


Figure 22. Profit contribution with no hedging

4.9. Conclusion and future research

This chapter of the dissertation develops a model that uses hedging strategies in a hybrid generation biofuel supply chain (HGBSC) setting. The hedging method considers a heuristic hedging strategy for purchasing corn and spot prices for purchasing cellulosic feedstocks, while ethanol end-product is hedged using futures. Non-hedging strategy uses spot prices for the purchase of both corn and cellulosic feedstock and sale of ethanol end-product. A two-stage stochastic linear programming method based on the Multi-cut Benders Decomposition Algorithm is used to solve the resulting model. The analyses show that hedging is better for lower profit realization and gives lower risk as compared to non-hedging. Also, non-hedging gives a higher profit realization with higher risk as compared to hedging. Also, the profit values for the non-hedging at lower profits are observed to be more risky as compared to the profit values of the hedged decisions.

One of the future studies that needs an urgent attention is to develop additional model or include a variance factor that will capture the value at risk at downside risk. The results indicate a large variance for the hedging as compared to non-hedging, meaning large profits will be penalized by huge variance which effectively measures risk. Therefore including a risk capturing function like a variability index or value at risk will add more managerial insight into the work.

Future research can consider where financial and operational decisions are made and reviewed, daily, weekly, or monthly which will reflect real time operation. Other future considerations will be adopting operational hedging based on inventory control, multiple suppliers, supply contracts, and lead time variability.

Additionally, using real data and comparing it to the analysis conducted in this research will be a good future direction. Real time data or historical data from sources like Bloomberg

and DTN will give added value to the novelty of the research and provide a better management insight.

Another consideration is using multi-period and multi-stage since this will reflect a better realization of the actual problem. Multi-period models provide better visibility in terms of inventory models and demand realizations. As inventory control becomes more visible, a daily, weekly, or monthly review of inventory will yield better profits.

Finally, additional uncertainties such as conversion rate might influence the optimal hedging strategies that will be used. Combination of hedging strategies such as future, options, and futures options will be a good research direction.

CHAPTER 5: MODELING SOCIAL SUSTAINABILITY AND CARBON TRADING IN HYBRID GENERATION BIOFUEL SUPPLY CHAIN UNDER UNCERTAINTIES

5.1. Abstract

This chapter of the dissertation develops a framework for the modeling and analysis of a hybrid-generation biofuel supply chain (HGBSC) with economic, social, and environmental decision-making as well as carbon trading. An optimization approach involving all the three sustainability concepts is considered. The biofuel supply chain consists of multiple sources of raw materials for corn and cellulosic feedstock, pre-treatment plants or warehouses, biorefineries, and demand zones. A two-stage stochastic mixed integer linear programming approach is used, where the first-stage binary decisions consider biorefinery location, capacity for warehouse, and capacity for biorefinery plants. The second-stage decisions include the amount of feedstock to purchase, the amount of feedstock to pre-treat, the amount of ethanol produced, the amount of ethanol sold, and the amount of greenhouse gas emission (GHG) emitted. The resulting model is solved using the Lagrangean Relaxation to relax the binary constraints and Sample Average Approximation (SAA) to solve the relaxed problem. The model seeks to maximize the profit of the supply chain and at the same time minimize the GHG, and maximize the corporate social responsibility output under uncertainties in ethanol price and raw material cost, and demand. A case study of a representative supply chain in North Dakota is considered. Further sensitivity analyses are conducted to determine the impact on profit for the entire supply chain by varying parameters such as demand and price of ethanol.

5.2. Introduction

Growing demand and emphasis on energy efficiency, sustainability, and cost reduction, have characterized the need for supply chains to improve in areas such as environmental and social sustainability. Currently, some businesses in general and supply chains in particular have become conscious of the need to incorporate sustainability as part of the decision making process, especially at the strategic level Gupta and Maranas (2010). There have also been criticisms as a result of increased effect of globalization from environmentalists on how environmental pollution affects water bodies in some societies. Consequently, supply chains have been called upon to increase greater responsibility towards social and environmental compliance in their operations Abdallah, Farhat, Diabat, and Kennedy (2012). Today, corporations are held accountable for the impact their entire supply chain activities have on the society and environment. Indeed, pressure from consumers, NGOs, local communities, legislatures, and regulatory bodies has affected how manufacturers or producers currently view sustainability Giarola, Shah, and Bezzo (2012).

When considering the biofuel supply chain for either profit maximization or cost minimization, it is important to consider sustainability within the decision making process Zhu, Li, and Huang (2013). The three main sustainability concepts that need to be considered are economic, environmental, and social responsibility. Although some literature have considered the integration of economic and social responsibility, such as Cruz (2011) and economic and environmental sustainability by Sundarakani, DeSouza, Goh, Wagner, and Manikandan (2010), not much attention has been channeled towards the integration of the three sustainability concepts under uncertainties. So far the paper by You, Tao, Graziano, and Snyder (2011) considered a cellulosic biofuel supply chain which combines the three sustainability concepts

with life cycle assessment (LCA). Nonetheless, no uncertainties are incorporated in the model presented. In view of this, we develop an HGBSC optimization model which considers these sustainability factors in an integrated fashion, while considering uncertainties in ethanol demand and price.

But there is dearth of papers in the combination of all the three sustainability concepts and also current literature uses a deterministic case as compared to the proposed stochasticity in ethanol price and demand in this dissertation. This dissertation seeks to solve this problem in a novel way by considering the following: (1) firstly integrating the entire sustainability concepts in the decision making process by considering social sustainability based on corporate social responsibility, (2) secondly, considering the economic sustainability as maximization of the supply chain profit under uncertainty in the ethanol price and demand, (3) thirdly, incorporating GHG emission permits purchases and sales, and (4) finally, modeling the problem as a two-stage stochastic problem and using the Lagrangean Relaxation technique with sub-gradient and SAA to solve the resulting problem.

Several papers dealing with biofuel supply chain optimization have been published. These papers are targeted at: (1) the supply chain network optimization, (2) maximization of profit, and (3) minimization of cost. Examples are Bazaraa and Sherali (1981), Eksioglu, Acharya, Leightly, and Arora (2009), Gronalt, and Rauch (2007), Kim, Realff, and Lee (2011), Jiao, Sua, Hou, and Liao (2012), and Zhang et al. (2012). There are also literature such as Cucek, Varbanov, Klemes, and Kravanja (2012) that incorporate economic and environment sustainability by maximizing the supply chain profit and calculating the environmental effect through classification into direct and indirect footprints. Other papers that have combined either of the sustainability concepts are as follows:

The work of Zamboni, Bezzo, and Shah (2009) considered an MILP static model with spatial characteristics that are explicit for the design of a bio-fuel supply chain at the strategic level. The paper further accounts for the concurrent minimization of cost while incorporating environmental sustainability concepts in terms of the GHG emissions.

Mele, Guillen-Gosalbez, and Jimenez (2009) addressed a planning problem of a biofuel supply chain with both environmental and economic integration. An optimization solution method based on the bicriterion MILP model was proposed for minimization of the total cost and its environmental concerns simultaneously. The results further analyze the performance over the entire life cycle of the sugar and ethanol.

Finally, the paper by You and Wang (2011) incorporated the successive optimization of a biomass-to- liquids supply chain based on life cycle optimization. The model is built based on the economic and environmental criteria. The results concluded an economically sound and environmentally friendly biomass processing supply chain when the model is implemented.

In the area of carbon emission trading, Cong and Wei's (2010) study the potential impact of the introduction of Carbon Emission Trading (CET) on China's power sector and discuss the impact of different allocation options of allowances. An agent-based modeling approach is used to solve the resulting problem. The paper concludes that incorporating the CET internalizes the environment cost as well as increases the average electricity price. Further results analyses indicate transfer carbon price volatility to the electricity market is realized which increases the electricity price volatility.

A full-infinite interval-stochastic mixed-integer programming (FIMP) is implemented by Zhu, Li, and Huang (2013) for planning carbon emission trading (CET) under dual uncertainties. The developed FIMP is applied to a real case study for managing carbon dioxide (CO₂)

emissions with trading scheme of Beijing's electric power system (EPS). The results show that the solutions for energy supply, electricity generation, carbon-quota allocation, and capacity expansion are not only needed but incorporated with policies and assessing economic impacts.

So far the paper that has direct carbon trading relationship in the ethanol industry is by Giarola, Shah, and Bezzo (2012). The authors used general mixed integer linear programming modeling framework which is developed to assess the design and planning of a multi-period and multi-echelon bioethanol upstream supply chain under market uncertainty. Results from the case study indicate the effectiveness of the model as a decision making-tool to steer long-term decisions and investments due to the ability of selecting a particular network. Other literature such as Austin (2007), Bojarski, Lainez, Espuna, and Puigjaner (2009), CGA (2009), Fisher (1985), Holicioglu (2009), Kocakr, Conejo, and McDonald (2009), Li, Yu, Luo, Ren, Dong, and Wong (2013), Sousa, Pinto, Rosa, and Mendes (2005), and Wagner (2004) have discussed carbon trading effects in other settings. Meanwhile, none has incorporated social corporate response (CSR) and carbon trading and solve using the lagrangean relaxation and Sample Average Approximation (SAA).

The rest of the section is organized as follows. Section 5.3 presents the problem statement. Section 5.4 proposes the mathematical model. In section 5.5, the proposed solution technique and uncertainties modeling is discussed. Additionally, section 5.6 discusses the case study followed by sensitivity analyses and summary of the case study results. Finally, conclusions and further research are presented in section 5.7.

5.3. Problem statement

Many decisions in the biofuel supply chain with the incorporation of sustainability will involve certain tradeoffs. An example in this case is making the decision to locate biorefinery

plants for both corn and cellulosic ethanol production. Because of such immediate tradeoffs, this paper considers profit maximization for the economic model including: 1) the binary decision to locate biorefinery facilities, 2) amount of corn and cellulosic feedstock that would be purchased from the supply sources, 3) amount of feedstock pre-treated 4) the amount of ethanol to be produced and 5) amount of produced ethanol that will be shipped to the demand zones.

A general structure of the supply chain consists of layers of biomass raw materials sources, pre-treatment plants, biorefinery plants, and demand zones. There are i_c number of raw material sources for corn feedstock, and i_m sources for cellulosic feedstock. Warehouse or pre-treatment plants for the respective feedstocks are w_c and w_m . The numbers of biorefinery plants are k_c for the corn ethanol, and k_m for the cellulosic ethanol plants. The end-product which is biofuel is represented by c_e and m_e for corn and cellulosic ethanol respectively.

The three aspects of sustainability are defined and modeled in the following problem as follows. Firstly, the economic concept considers the profit maximization in the biofuel supply chain. Secondly, the environmental sustainability considers GHG for transportation or raw materials from the supply sources, pre-treatment plants, biorefinery plants, and the demand zones. Finally, sustainability from the social perspective considers maximizing of social benefits based on some threshold of investments.

First-stage decision consists of determining the location of biorefinery plants, capacity of warehouses, and the capacity of the biorefinery plants. Second-stage decisions on the other hand consists of the amount of cellulosic and corn feedstock purchased, the amount of feedstock pre-treated, the amount of ethanol produced, the amount of ethanol sold, and the amount of co-products produced. Other sustainable decisions such as the GHG emission produced, excess amount of emission, extra amount of emission, and the number of corporate social responsibility

projects built are also considered. Input parameters that include feedstock, warehouse, ethanol production, and transportation, and other costs are also provided.

A policy for GHG emission considers the amount of GHG that is emitted per scenario or period as well as any excess and extra amount of GHG to be sold or purchased respectively. The total GHG emission in the entire supply chain is considered as a decision variable. In this case, two main constraints are provided. First the total carbon emitted in the supply chain plus any excess amount of GHG permit left will exceed the GHG for the entire permits available for purchase in any time period. Secondly, the total GHG emitted in the supply chain minus any extra GHG permits will be less than or equal to the total emission purchased or allowed for the supply chain.

The objective function seeks to maximize the supply chain profit by considering the revenue generated from the sale of ethanol and by-products, while considering costs from raw material purchase, transportation, and production. Some novel ideas that this dissertation brings are: 1) Incorporating carbon emission trading, 2) Integrating environmental and social sustainability decisions in the economic model, 3) Using Lagrangean relaxation and Sample Average Approximation (SAA) to solve the resulting problem.

Diagram illustrating the supply chain, and its activities as well as the mathematical equations are provided in the next section.

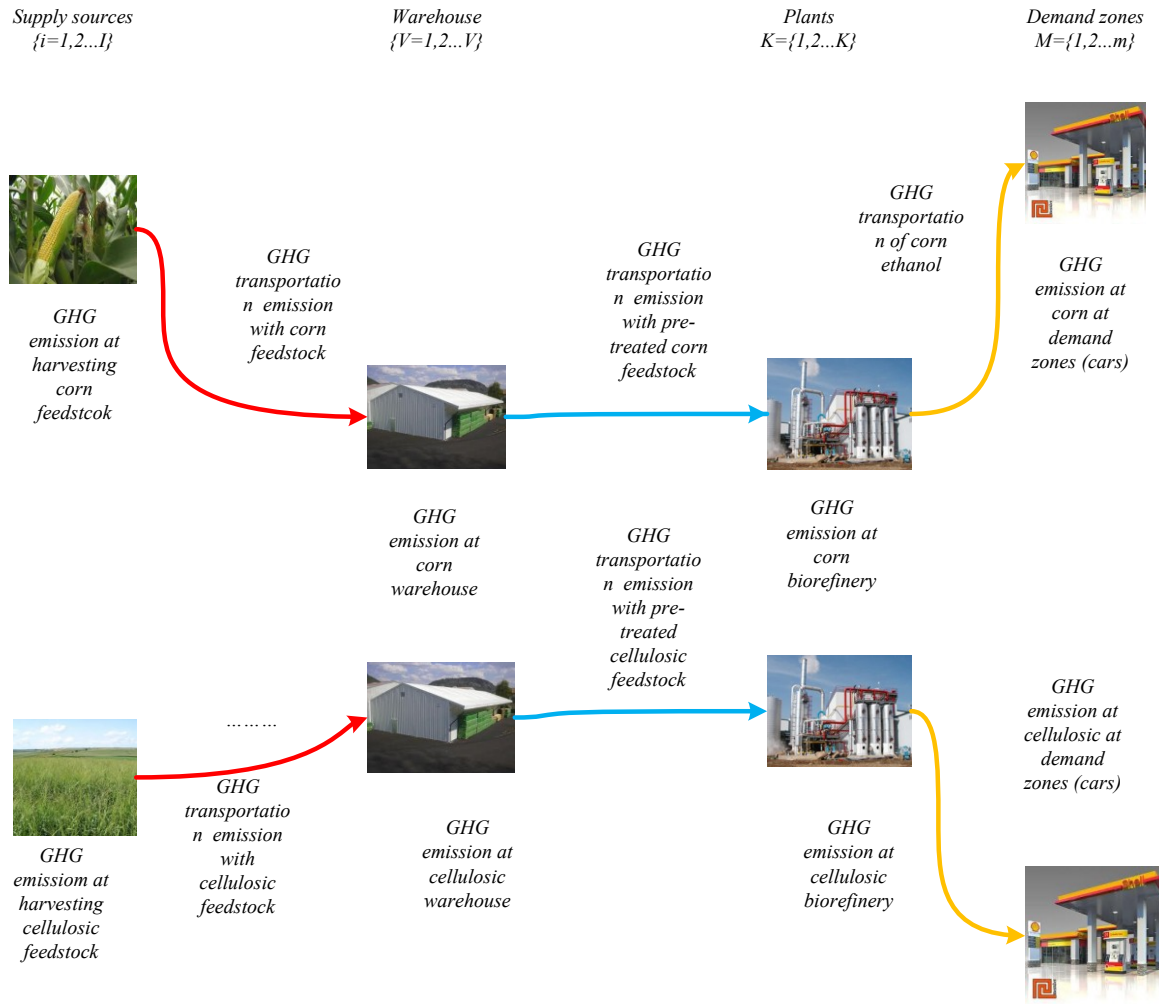


Figure 23. Typical biofuel supply chain network

5.4. Mathematical model

In this work, we first propose a mathematical model which first of all considers economic sustainability by maximizing the profit of the supply chain. Secondly, an optimization model which seeks to minimize the GHG effect of the environment is also considered. Finally, maximizing the social benefits using corporate social responsibility is then analyzed. The next section provides the indexes of the set, decision variable, and parameters for the model.

Indices/Sets:

i_c	The index of corn feedstock supply source $i_c = 1, 2 \dots I_c$
i_m	The index of cellulosic feedstock supply source $i_m = 1, 2 \dots I_m$
w_c	The index of warehouse for storing corn feedstock $w_c = 1, 2, \dots I_c$
w_m	The index of warehouse for storing cellulosic feedstock $w_m = 1, 2, \dots I_c$
tm	The index for trading or selling market $tm = 1, 2, 3 \dots TM$
k_c	The index of corn biorefinery plant $k_c = 1, 2, 3 \dots KC$
k_m	The index of cellulosic biorefinery plant $k_c = 1, 2, 3 \dots KM$
c_f	The index of corn feedstock index
c_e	The index of corn ethanol index
m_f	The index of cellulosic feedstock index
m_e	The index of cellulosic ethanol index
t	The index of time horizon for the entire period of planning $t = 1, 2, \dots T$
ξ	The index of scenario for the uncertainty
q	The index of location for biorefinery $q = 1, 2, \dots Q$
tb	The index for the type of biorefinery $tb = 1, 2, \dots TB$

Deterministic parameters

$PC_{k_c, t}$	Production cost of corn ethanol at plant k_c in time period t
$PM_{k_m, t}$	Production cost of cellulosic ethanol at plant k_m in time period t
$H_{c_f, t}^{w_c}$	Inventory holding cost for corn feedstock c_f at warehouse w_c at time period t
$H_{m_f, t}^{w_m}$	Inventory holding cost for cellulosic feedstock m_f at warehouse w_m in time t

$H_{c_e, t}^{k_c}$	Inventory cost for corn ethanol c_e at plant k_c in time period t
$H_{m_e, t}^{k_m}$	Inventory cost for cellulosic ethanol m_e at plant k_m in time period t
$T_{c_f, t}^{i_c, w_c}$	Transportation cost for corn feedstock c_f from supplier source i_c to warehouse w_c in time period t
$T_{m_f, t}^{i_m, w_m}$	Transportation cost for cellulosic feedstock m_f from supplier i_m to warehouse w_m in time period t
$T_{c_f, t}^{w_c, k_c}$	Transportation cost for corn feedstock c_f from warehouse w_c to biorefinery k_c in time period t
M_c	The cost of building a biorefinery plant
$T_{m_f, t}^{w_m, k_m}$	Transportation cost for cellulosic feedstock m_f from warehouse w_m to biorefinery k_m in period t
$T_{c_e, t}^{k_c, tm}$	Transportation cost for corn ethanol c_e from biorefinery k_c to trade market tm in time period t
$T_{m_e, t}^{k_m, tm}$	Transportation cost for cellulosic ethanol m_e from biorefinery k_m to market tm in time period t
$dc_{c_f, t}^{i_c, w_c}$	Transportation distance for corn feedstock c_f from supply source i_c to warehouse w_c in time t
$dc_{c_f, t}^{w_c, k_c}$	Transportation distance for corn feedstock c_f from warehouse w_c to biorefinery k_c in time period t
$dc_{c_e, t}^{k_c, tm}$	Transportation distance for corn ethanol c_e from biorefinery k_c to trade market tm in time period t
$dm_{m_f, t}^{i_m, w_m}$	Transportation distance for cellulosic feedstock m_f from source i_m to warehouse

	w_m in time period t
$dm_{m_f, t}^{w_m, k_m}$	Transportation distance for cellulosic feedstock m_f from warehouse w_m to plant k_m in time period t
	k_m in time period t
$dm_{m_e, t}^{k_m, cm}$	Transportation distance for cellulosic ethanol m_e from plant k_m to trade market cm in time period t
	cm in time period t
β	Corn ethanol conversion rate
∂_{fl}	Conversion factor from cellulosic feedstock to lignin at refinery plant
λ	Cellulosic ethanol conversion rate
∂_{fp}	Conversion factor from cellulosic feedstock to protein at refinery plant
∇_{cd}	Conversion factor from corn feedstock to DDGS at refinery plant
∇_{co}	Conversion factor from cellulosic feedstock to corn oil at refinery plant
α	Initial corporate sustainability value of economic benefit
M_q	Cost of installing biorefinery per location
$Capf_{wco} \min$	Minimum fixed capacity of corn warehouse
$Capf_{wco} \max$	Maximum fixed capacity of corn warehouse
$Capf_{wce} \min$	Minimum fixed capacity of cellulosic warehouse
$Capf_{wce} \max$	Maximum fixed capacity of cellulosic warehouse
$Capf_{kco} \min$	Minimum fixed capacity of corn biorefinery plant
$Capf_{kco} \max$	Maximum fixed capacity of corn biorefinery plant
$Capf_{kce} \min$	Minimum fixed capacity of cellulosic biorefinery plant
$Capf_{kce} \max$	Maximum fixed capacity of cellulosic biorefinery plant
$Capv_{wco} \min$	Minimum variable capacity of corn warehouse

$Capv_{wco}$ max Maximum variable capacity of corn warehouse

$Capv_{wce}$ min Minimum variable capacity of cellulosic warehouse

$Capv_{wce}$ max Maximum variable capacity of cellulosic warehouse

$Capv_{kco}$ min Minimum variable capacity of corn biorefinery plant

$Capv_{kco}$ max Maximum variable capacity of corn biorefinery plant

$Capv_{kce}$ min Minimum variable capacity cellulosic biorefinery plant

$Capv_{kce}$ max Maximum variable capacity cellulosic biorefinery plant

Stochastic parameters

$C_{c_f, t}^{\xi, i_c}$ Uncertain cost of purchasing corn feedstock c_f from supplier i_c in time period t
under scenario ξ

$P_{c_e, t}^{\xi, tm}$ Price of corn ethanol c_e sold under scenario ξ in time period t to market tm

$C_{m_f, t}^{\xi, i_m}$ Uncertain cost of purchasing cellulosic feedstock m_f from supplier i_m in time period

$P_{m_e, t}^{\xi, tm}$ Price of cellulosic ethanol m_e sold under scenario ξ in time period t to market tm

$d_{c_e, t}^{tm, \xi}$ Demand for corn ethanol c_e at trade market tm in time period t

$d_{m_e, t}^{cm, \xi}$ Demand for cellulosic ethanol c_m at cash market m_e in time period t

$Pcd_{c_e, t}^{\xi, tm}$ Price of DDGS per gallon

$Pco_{c_e, t}^{\xi, tm}$ Price of corn oil per ton

$Pl_{m, t}^{\xi, cm}$ Price of lignin per ton

$Pp_{m, t}^{\xi, cm}$ Price of protein per ton

Sustainability parameters and variables (first and second stage)

GHG_{co1}	Cost of corn GHG emission from the supply source to warehouse
GHG_{co2}	Cost of corn GHG emission at the warehouse
GHG_{co3}	Cost of corn GHG emission from the warehouse to ethanol plants
GHG_{co4}	Cost of corn GHG emission at the ethanol plants
GHG_{co5}	Cost of corn GHG emission from the ethanol plants to demand zones
$Ce_{tb,q}$	Profit from investing in a sustainability project for biorefinery tb in location q
GHG_{ce1}	Cost of cellulosic GHG emission from the supply source to warehouse
GHG_{ce2}	Cost of cellulosic GHG emission at the warehouse
GHG_{ce3}	Cost of cellulosic GHG emission from the warehouse to ethanol plants
GHG_{ce4}	Cost of cellulosic GHG emission at the ethanol plants
GHG_{ce5}	Cost of cellulosic GHG emission from the ethanol plants to demand zones
$Cg_{tb,q}$	Cost of investing in a sustainability project for biorefinery tb in location q
$Excess(\xi)$	Excess amount of GHG left (to sell) during the production/mandate period
$Extra(\xi)$	Extra amount of GHG needed (to buy) during the production/mandate period
$XCSR_{tb,q}$	Decisions for sustainability projects (hospital, community center, and school)

Emission trading (ET) parameters and variables

$Cs(\xi)$	Carbon emission coefficient cost purchases for the entire supply chain
$Carbon(\xi)$	Total GHG emitted in the entire supply chain per scenario ξ

TTE Emission level allowed for the supply chain (this is like permit level)

First-stage decision variables

$Y_{tb,c,q}$ = {1, if biorefinery plant type tb , with capacity c is built in location q ; Else its is 0}

$W_{tb,c,q}$ A warehouse installed at a biorefinery of type tb , with capacity c in location q

$Xc_{c_f,t}^{w_c}$ Capacity of corn warehouse w_c for pre-treating feedstock m_c in time period t

$Xc_{m_f,t}^{w_m}$ Capacity of cellulosic warehouse w_m for pre-treating feedstock m_f in time period t

$VCap_{k_c,t}$ Production capacity of corn ethanol at plant k_c in time period t

$VCap_{k_m,t}$ Production capacity of cellulosic ethanol at plant k_m in time period t

Second-stage decision variables

$x_{i_c,t}^{w_c,\xi}$ Corn feedstock purchased from source i_c for warehouse w_c at time t under scenario ξ

$x_{i_m,t}^{w_m,\xi}$ Cellulosic feedstock from source i_m for warehouse w_m at time t under scenario ξ

$S_{c_i,t}^{\xi,tm}$ Corn ethanol m_e sold in scenario ξ at time t for trade market tm

$S_{m_e,t}^{\xi,tm}$ Cellulosic ethanol m_e sold in scenario ξ at time t for trade market tm

$z_{k_c,t}^{tm,\xi}$ Corn ethanol produced at plant k_c at time t for trade market tm under scenario ξ

$z_{k_m,t}^{tm,\xi}$ Cellulosic ethanol produced at plant k_m at time t for trade market tm under scenario ξ

$I_{c_e,t}^{\xi,k_c}$ Corn ethanol c_e inventory held at plant k_c in time t under scenario ξ

$I_{m_e,t}^{\xi,k_m}$ Cellulosic ethanol m_e inventory held at plant k_m in time period t under scenario ξ

$I_{c_f,t}^{\xi,w_c}$ Corn inventory of feedstock c_f at warehouse w_c in time period t under scenario ξ

$I_{m_f,t}^{\xi,w_m}$ Cellulosic inventory of feedstock m_f at warehouse w_m in time t under scenario ξ

$CL_{m_e,t}^{k_m,\xi}$ Amount of lignin produced from cellulosic feedstock at plant k_m in time period t

$CP_{m_e,t}^{k_m,\xi}$ Amount of protein produced from cellulosic at plant k_m in time period t

$CD_{c,t}^{k_m,\xi}$ Amount of DDGS produced from corn at plant k_c in time period t

$CO_{c,t}^{k_m,\xi}$ Amount of corn oil produced from corn at plant k_c in time period t

$XP_{c_f,t}^{w_c,\xi}$ Pre-treated corn feedstock c_f available at warehouse w_c in time period t under scenario ξ

$XP_{m_f,t}^{w_m,\xi}$ Pre-treated cellulosic feedstock m_f at warehouse w_m in time period t under scenario ξ

5.4.1 Objective function mathematical model

This section introduces the objective function and constraints for the first part which proposes a mathematical model for the economic objective function maximization.

Objective function: Economic sustainability

The objective function seeks to maximize the total sustainable benefits of the supply chain which includes economic, environmental, and social benefits. The economic benefit comprises from selling ethanol and its related by-products and the costs such as raw materials purchase and transportation. Environmental sustainability benefits involve emission trading, which consists of buying and selling GHG permits. Finally, the social sustainability benefits consider corporate social responsibility projects that are invested in by the biorefinery plants.

$$Max Z_1 = Rc + Rce + Rdgs + Rco + Rlig + Rprot - Bfc - Cco - Ico - Pco1 - Capco - Pco2 - Tco1 - Tco2 - Tco3 - Cce - Ice - Pce1 - Capce - Pce2 - Tce1 - Tce2 - Tce3 - GHGrc + CSRrc \quad (5.1)$$

Revenue of corn and cellulosic sales

Rc is the revenue obtained by selling corn ethanol c_e at the trade market tm for time period t

$$Rc = E_{\xi} \left(\sum_{k_c \in KC} \sum_{tm \in TM} \sum_{t \in T} P_{c_e,t}^{\xi, tm} S_{c_e,t}^{\xi, tm} \right) \quad (5.1a)$$

Rce is the revenue of selling cellulosic ethanol m_e at the trade market cm for time period t

$$Rce = E_{\xi} \left(\sum_{k_m \in KM} \sum_{c_m \in CM} \sum_{t \in T} P_{m_e, t}^{\xi, tm} S_{m_e, t}^{\xi, cm} \right) \quad (5.1b)$$

Rdgs is the revenue by selling DDGS produced at plant k_c sold to cash market cm for period t

$$Rdgs = E_{\xi} \left(\sum_{k_c \in KC} \sum_{tm \in TM} \sum_{t \in T} Pcd_{c_e, t}^{\xi, tm} CD_{c, t}^{k_m, \xi} \right) \quad (5.1c)$$

Rco is the revenue of selling corn oil produced at plant k_m , sold at market cm at time period t

$$Rco = E_{\xi} \left(\sum_{k_c \in KC} \sum_{tm \in TM} \sum_{t \in T} Pco_{c_e, t}^{\xi, tm} CD_{c, t}^{k_m, \xi} \right) \quad (5.1d)$$

Rlig is the revenue of selling lignin produced and sold on the cash market cm for period t

$$Rlig = E_{\xi} \left(\sum_{k_m \in KM} \sum_{tm \in TM} \sum_{t \in T} Pl_{m_e, t}^{\xi, tm} CL_{m, t}^{k_m, \xi} \right) \quad (5.1e)$$

Rprot is the revenue of selling protein produced sold to the trade market cm at time period t

$$Rprot = E_{\xi} \left(\sum_{k_c \in KC} \sum_{tm \in TM} \sum_{t \in T} Pp_{m_e, t}^{\xi, tm} CP_{m, t}^{k_m, \xi} \right) \quad (5.1f)$$

Cost for corn

Cco is the cost of corn feedstock purchased from supply source i_c to warehouse w_c at period t

$$Cco = E_{\xi} \left(\sum_{w_c \in WC} \sum_{t \in T} C_{c_f, t}^{i_c, \xi} X_{i_c, t}^{w_c, \xi} \right) \quad (5.1g)$$

Ico is the fixed and variable inventory cost for corn feedstock c_f at warehouse w_c at period t

$$Ico = E_{\xi} \left(\sum_{w_c \in WC} \sum_{t \in T} W_v X_{c_f, t}^{w_c, \xi} \right) + \sum_{w_c \in WC} \sum_{t \in T} H_{c_f, t}^{w_c} X_{c_f, t}^{w_c} \quad (5.1h)$$

Pco1 is the pre-treatment cost of corn feedstock at the warehouse for the time period t

$$Pco1 = E_{\xi} \left(\sum_{k_c \in KC} \sum_{t \in T} H_{c_e, t}^{k_c} Xc_{c_f, t}^{w_c} \right) \quad (5.1i)$$

Capco is the fixed and variable capacity cost for corn ethanol production in time period t

$$Capco = E_{\xi} \left(\sum_{w_c \in WC} \sum_{t \in T} C_v Cap_{k_c, t}^{\xi} \right) + \sum_{w_c \in WC} \sum_{t \in T} H_{c_f, t}^{w_c} Cap_{k_c, t} \quad (5.1j)$$

Pco2 is the cost of production of corn ethanol c_e at plant k_c in time period t

$$Pco2 = E_{\xi} \left(\sum_{k_c \in KC} \sum_{t \in T} PC_{k_c, t} z_{k_e, t}^{tm, \xi} \right) \quad (5.1k)$$

Tco1 is the transportation cost of corn feedstock from supply source i_c to warehouse w_c

$$Tco1 = E_{\xi} \left(\sum_{i_c \in IC} \sum_{w_c \in WC} \sum_{t \in T} T_{c_f, t}^{i_c, w_c} dc_{c_f, t}^{i_c, w_c} x_{i_c, t}^{w_c, \xi} \right) \quad (5.1l)$$

Tco2 is the transportation cost of corn feedstock from warehouse w_c to biorefinery k_c

$$Tco2 = E_{\xi} \left(\sum_{w_c \in WC} \sum_{k_c \in KC} \sum_{t \in T} T_{c_f, t}^{w_c, k_c} dc_{c_f, t}^{w_c, k_c} Xp_{c_f, t}^{w_c, \xi} \right) \quad (5.1m)$$

Tco3 is the transportation cost of corn ethanol from biorefinery k_c to market tm in time period t

$$Tco3 = E_{\xi} \left(\sum_{k_c \in KC} \sum_{t_m \in TM} \sum_{t \in T} T_{c_e, t}^{k_c, tm} dc_{c_e, t}^{k_c, tm} z_{k_c, t}^{tm, \xi} \right) \quad (5.1n)$$

Cost for cellulosic

Cce is the total cost of cellulosic feedstock that are purchased from supply source i

$$Cce = E_{\xi} \left(\sum_{w_m \in WM} \sum_{t \in T} C_{m_f, t}^{i_m, \xi} x_{i_m, t}^{w_m} \right) \quad (5.1o)$$

Ice is the fixed and variable inventory holding cost for cellulosic feedstock which is given by

$$Ice = E_{\xi} \left(\sum_{w_m \in WM} \sum_{t \in T} W_v Xc_{m_f, t}^{w_m, \xi} \right) + \sum_{w_m \in WM} \sum_{t \in T} H_{m_f, t}^{w_m} Xc_{m_f, t}^{w_m} \quad (5.1p)$$

Pce is the pre-treatment or holding cost of cellulosic feedstock at the warehouse

$$Pce = E_{\xi} \left(\sum_{k_m \in KM} \sum_{t \in T} H_{m_e, t}^{k_m} Xc_{m_f, t}^{w_m} \right) \quad (5.1q)$$

Cce is the fixed and variable capacity cost for corn ethanol production in time period t

$$Cce = E_{\xi} \left(\sum_{w_c \in WC} \sum_{t \in T} C_v Cap_{k_m, t}^{\xi} \right) + \sum_{w_c \in WC} \sum_{t \in T} H_{c_f, t}^{w_c} Cap_{k_m, t} \quad (5.1r)$$

Pce1 is the cost of cellulosic production for the entire particular time period which is given by

$$Pce1 = E_{\xi} \left(\sum_{k_m \in KM} \sum_{t \in T} PC_{k_m, t} z_{k_m, t}^{tm, \xi} \right) \quad (5.1s)$$

Tce1 is the transportation cost of cellulosic feedstock from supply source to warehouse w_m

$$Tce1 = E_{\xi} \left(\sum_{i_m \in IM} \sum_{w_m \in WM} \sum_{t \in T} T_{m_f, t}^{i_m, w_m} dc_{m_f, t}^{i_m, w_m} x_{i_m, t}^{w_m, \xi} \right) \quad (5.1t)$$

Tce2 is transportation cost of cellulosic feedstock from warehouse to biorefinery k

$$Tce2 = E_{\xi} \left(\sum_{w_m \in WM} \sum_{k_m \in KM} \sum_{t \in T} T_{m_f, t}^{w_m, k_m} dc_{m_f, t}^{w_m, k_m} Xp_{m_f, t}^{w_m, \xi} \right) \quad (5.1u)$$

Tce3 is transportation cost of cellulosic ethanol from biorefinery to demand zones

$$Tce3 = E_{\xi} \left(\sum_{k_m \in KM} \sum_{cm \in CM} \sum_{t \in T} T_{m_e, t}^{k_m, cm} dc_{m_e, t}^{k_m, cm} z_{k_m, t}^{tm, \xi} \right) \quad (5.1v)$$

Carbon emission trading revenue and cost

GHGrc is the penalty cost of emitting GHG for the entire biorefinery supply chain

$$GHGrc = Cs(\xi) * Carbon(\xi) \forall \xi \quad (5.1w)$$

Corporate social responsibility

CSRrc is the revenue and cost of investing in corporate social responsibility projects

$$CSRrc = XCSR_{tb,q} \left(\sum_{tb \in TB} \sum_{q \in Q} Ce_{tb,q} - \sum_{tb \in TB} \sum_{q \in Q} Cg_{tb,q} \right) \forall tb, \forall q \quad (5.1x)$$

Cost of installing a biorefinery plant

Bfc is the cost of buying and installing or building a biorefinery plant of capacity c in location q

$$Bfc = \sum_{q=1}^Q M_q Y_{tb,c,q} \forall q, \forall tb, \forall c \quad (5.1y)$$

Cost of installing a warehouse at a biorefinery plant

Whc is the cost of installing or hiring a warehouse or pre-treatment plant

$$Whc = \sum_{q=1}^Q Cw_q W_{tb,c,q} \forall q, \forall tb, \forall c \quad (5.1z)$$

Subject to:

Warehouse capacity constraints

Equation 5.2 ensures the total amount of corn feedstock supplied from the sources to the warehouse should be less than or equal to the amount available at the sources

$$\sum_{i_c \in IC} x_{i_c,t}^{w_c,\xi} \leq Xp_{c,f,t}^{w_c,\xi} \forall k_c, \forall c, \forall t \quad (5.2)$$

Equation 5.3 ensures the total amount of cellulosic feedstock supplied from the source to the warehouse should be less than or equal to the amount available at the sources

$$\sum_{i_m \in IM} x_{i_m,t}^{w_m,\xi} \leq Xp_{m,f,t}^{w_m,\xi} \forall k_m, \forall m, \forall t \quad (5.3)$$

Demand, sales, capacity and production constraints

Equation 5.4 ensures the amount of corn ethanol sold to each trade market cannot be more than the market demand at a given time period.

$$S_{c_e,t}^{\xi,tm} \leq d_{c_e,t}^{tm,\xi} \forall c_e, \forall tm, \forall \xi, \forall t \quad (5.4)$$

Equation 5.5 ensures the amount of cellulosic ethanol sold to the market cannot be more than the market demand at a given time period.

$$S_{m_e,t}^{\xi,tm} \leq d_{m_e,t}^{cm,\xi} \quad \forall m_e, \forall tm, \forall \xi, \forall t \quad (5.5)$$

Equation 5.6 ensures the amount of corn ethanol produced should be at least as much as the amount sold in any given time period.

$$z_{k_c,t}^{tm,\xi} \leq 0.45D_t \quad \forall k_c, \forall tm, \forall \xi, \forall t \quad (5.6)$$

Equation 5.7 ensures the amount of cellulosic ethanol produced should be at least as much as the amount sold in any given time period.

$$z_{k_m,t}^{tm,\xi} \geq 0.55D_t \quad \forall k_m, \forall tm, \forall \xi, \forall t \quad (5.7)$$

Equation 5.8 is the total production from corn and cellulosic which is equal to the total demand

$$z_{k_c,t}^{tm,\xi} + z_{k_m,t}^{tm,\xi} \geq D_t \quad \forall k_m, \forall k_c, \forall tm, \forall \xi, \forall t \quad (5.8)$$

Equation 5.9 total production from corn and cellulosic demand should be equal to total demand

$$d_{c_e,t}^{tm,\xi} + d_{m_e,t}^{cm,\xi} = D_t \quad \forall c_e, \forall m_e, \forall tm, \forall \xi, \forall t \quad (5.9)$$

Equation 5.10 ensures the amount of corn ethanol produced should be always less than the ethanol plant production capacity.

$$z_{k_c,t}^{tm,\xi} \leq VC_{k_c,t} \quad \forall k_c, \forall tm, \forall \xi, \forall t \quad (5.10)$$

Equation 5.11 ensures the amount of cellulosic ethanol produced should be always less than the cellulosic plant production capacity.

$$z_{k_m,t}^{tm,\xi} \leq VC_{k_m,t} \quad \forall k_m, \forall tm, \forall \xi, \forall t \quad (5.11)$$

Fixed capacity constraints

Equation 5.12 is the capacity of corn based warehouse

$$Capf_{wco} \min \leq Xc_{c_f,t}^{k_c} \leq Capf_{wco} \max \quad \forall c_f, \forall k_c, \forall wco, \forall t \quad (5.12)$$

Equation 5.13 is the capacity of cellulosic based warehouse

$$Capf_{wce} \min \leq Xc_{m_f,t}^{k_m} \leq Capf_{wce} \max \forall m_f, \forall k_m, \forall wce, \forall t \quad (5.13)$$

Equation 5.14 is the capacity of corn based biorefinery

$$Capf_{kco} \min Y_{c,q} \leq VCap_{k_c,t} \leq Capf_{kco} \max Y_{c,q} \forall c, \forall q, \forall k_c, \forall kco, \forall t \quad (5.14)$$

Equation 5.15 is the capacity of cellulosic based biorefinery

$$Capf_{kce} \min Y_{c,q} \leq VCap_{k_m,t} \leq Capf_{kce} \max Y_{c,q} \forall c, \forall q, \forall k_m, \forall kce, \forall t \quad (5.15)$$

Variable capacity constraints

Equation 5.16 is the variable capacity of corn based warehouse

$$Capv_{wco} \min \leq Xc_{c_f,t}^{k_c} \leq Capv_{wco} \max \forall c_f, \forall k_c, \forall wco, \forall t \quad (5.16)$$

Equation 5.17 is the variable cost of cellulosic based warehouse

$$Capv_{wce} \min \leq Xc_{m_f,t}^{k_m} \leq Capv_{wce} \max \forall m_f, \forall k_m, \forall wce, \forall t \quad (5.17)$$

Equation 5.18 is variable cost of the capacity of corn based biorefinery

$$Capv_{kco} \min Y_{c,q} \leq VCap_{k_c,t} \leq Capv_{kco} \max Y_{c,q} \forall c, \forall q, \forall k_c, \forall kco, \forall t \quad (5.18)$$

Equation 5.19 is the variable capacity of cellulosic based biorefinery

$$Capv_{kce} \min Y_{c,q} \leq VCap_{k_m,t} \leq Capv_{kce} \max Y_{c,q} \forall c, \forall q, \forall k_m, \forall kce, \forall t \quad (5.19)$$

Feedstock conversion constraints

Equation 5.20 ensures the amount of corn ethanol produced is proportional to the rate of conversion of the feedstock.

$$z_{k_c,t}^{m,\xi} = \beta(Xp_{c_f,t}^{w_c,\xi}) \forall k_c, \forall w_c, \forall \xi, \forall c_f, \forall tm, \forall t \quad (5.20)$$

Equation 5.21 ensures the amount of cellulosic ethanol produced is proportional to the rate of conversion in the products production.

$$z_{k_m,t}^{m,\xi} = \lambda(Xp_{m_f,t}^{w_m,\xi}) \forall k_m, \forall w_m, \forall \xi, \forall m_f, \forall t \quad (5.21)$$

Equation 5.22 ensures the amount of corn feedstock pretreated and transported to corn biorefinery plants is less or equal to the plant capacity.

$$\sum_{w_c \in W_C} Xp_{c_f,t}^{w_c,\xi} \leq VCap_{k_c,t} \forall k_m, \forall w_c, \forall \xi, \forall m_f, \forall t \quad (5.22)$$

Equation 5.23 ensures the amount of cellulosic feedstock pretreated transported to biorefinery plants is less or equal to the plant capacity.

$$\sum_{w_m \in W_M} Xp_{m_f,t}^{w_m,\xi} \leq VCap_{k_f,t} \forall k_m, \forall w_m, \forall \xi, \forall m_f, \forall t \quad (5.23)$$

End-product constraints

Equation 5.24 ensures the amount of lignin produced is proportional to the rate of consumption of the cellulosic feedstock.

$$\partial_{fl}(Xp_{m_f,t}^{w_m,\xi}) = CL_{m_e,t}^{k_m,\xi} \forall k_m, \forall m_e, \forall w_m, \forall \xi, \forall m_f, \forall t \quad (5.24)$$

Equation 5.25 ensures the amount of protein produced is proportional to the rate of consumption of the cellulosic feedstock.

$$\partial_{fp}(Xp_{m_f,t}^{w_m,\xi}) = CP_{m_e,t}^{k_m,\xi} \forall k_m, \forall m_e, \forall w_m, \forall \xi, \forall m_f, \forall t \quad (5.25)$$

Equation 5.26 ensures the amount of DDGS produced is proportional to the rate of consumption of the corn feedstock.

$$\nabla_{cd}(Xp_{c_f,t}^{w_c,\xi}) = CD_{c,t}^{k_m,\xi} \forall k_m, \forall m_e, \forall w_c, \forall \xi, \forall c_f, \forall t \quad (5.26)$$

Equation 5.27 ensures the amount of corn oil produced is proportional to the rate of consumption of the corn feedstock.

$$\nabla_{cco}(Xp_{c_f,t}^{w_c,\xi}) = CO_{c,t}^{k_m,\xi} \forall k_m, \forall m_e, \forall w_c, \forall \xi, \forall c_f, \forall t \quad (5.27)$$

GHG emission constraints

Equations 5.28 GHG emission for the entire supply chain

$$\begin{aligned}
& \sum_{i_m \in IM} \sum_{w_m \in WM} \sum_{t \in T} GHG_{co1} (T_{m_f,t}^{i_m,w_m} dc_{m_f,t}^{i_m,w_m} x_{i_m,t}^{w_m,\xi}) + \sum_{w_c \in WC} \sum_{k_c \in KC} \sum_{t \in T} GHG_{co2} (T_{c_f,t}^{w_c,k_c} dc_{c_f,t}^{w_c,k_c} Xp_{c_f,t}^{w_c,\xi}) + \\
& \sum_{t=1}^T \sum_{i=1}^I \sum_{k=1}^K GHG_{co3} c_{i,k}^t z_{k_m,t}^{cm,\xi} + \sum_{k_m \in KM} \sum_{cm \in CM} \sum_{t \in T} GHG_{co4} (T_{m_e,t}^{k_m,cm} dc_{m_e,t}^{k_m,cm} z_{k_m,t}^{cm,\xi}) + \sum_{k_m \in KM} \sum_{cm \in CM} \sum_{t \in T} GHG_{co5} (p_{m_e,t}^{k_m,cm} z_{k_m,t}^{cm,\xi}) \\
& + \sum_{k_m \in KM} \sum_{cm \in CM} \sum_{t \in T} GHG_{co6} (w_{m_e,t}^{k_m,cm} z_{k_m,t}^{cm,\xi}) = \text{Carbon}(\xi) \quad \forall k_m, \forall m_e, \forall w_c, \forall \xi, \forall c_f, \forall t
\end{aligned} \tag{5.28}$$

Equation 5.29 GHG emission for the entire supply chain

$$\text{Carbon}(\xi) + \text{Excess}(\xi) = \text{TTE} + \text{Extra}(\xi) \quad \forall \xi \tag{5.29}$$

Equation 5.30 GHG constraint for excess emission

$$\text{Carbon}(\xi) + \text{Excess}(\xi) \geq \text{TTE} \quad \forall \xi \tag{5.30}$$

Equation 5.31 GHG constraint for extra emission

$$\text{Carbon}(\xi) - \text{Extra}(\xi) \leq \text{TTE} \quad \forall \xi \tag{5.31}$$

Social sustainability constraints

Equation 5.32 sustainability constraint for social sustainability investment

$$\sum_{tb \in TB} \sum_{q \in Q} Cg_{tb,q} XCSR_{tb,q} \leq \alpha * Z_2 \quad \forall tb, \forall q \tag{5.32}$$

where $Z_2 = Z_1 - CSRrc$

Equation 5.33 constraint for building a biorefinery at any location

$$Y_{tb,c,q} \leq 1 \quad \forall tb, \forall q, \forall qc \tag{5.33}$$

Equation 5.34 constraint for sales and amount produced corn biorefinery

$$S_{c_e,t}^{\xi,m} \geq z_{k_c,t}^{m,\xi} \quad \forall k_c, \forall c_e, \forall \xi, \forall tm, \forall t \tag{5.34}$$

Equation 5.35 constraint for sales and amount produced for cellulosic biorefinery

$$S_{m_e,t}^{\xi,m} \geq z_{k_m,t}^{m,\xi} \forall k_m, \forall m_e, \forall \xi, \forall t, \forall m \quad (5.35)$$

Equation 5.36 constraint for warehouse installation at a plant

$$W_{b,c,q} = Y_{b,c,q} \forall b, \forall c, \forall q \quad (5.36)$$

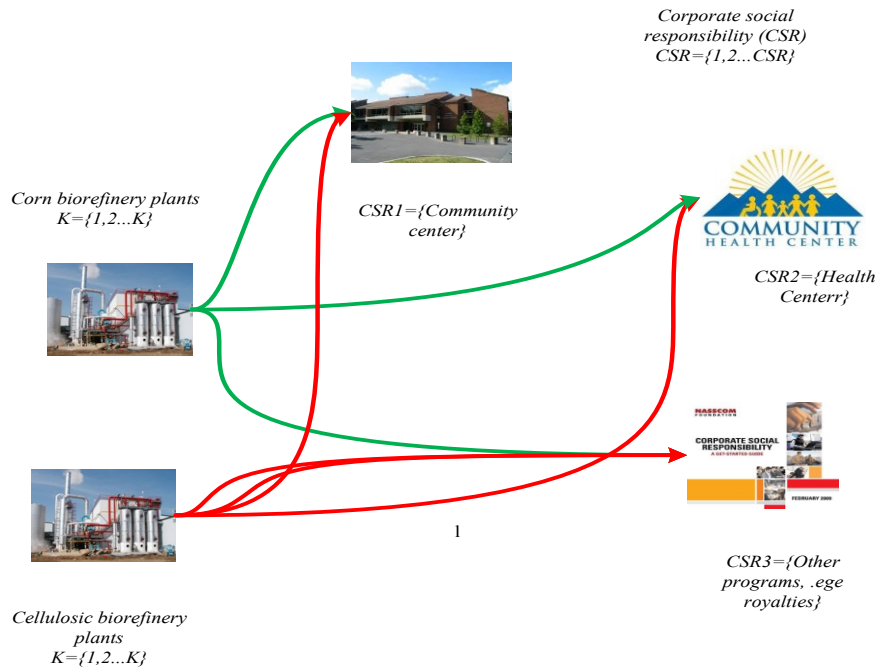


Figure 24. Sustainability network for the biorefinery plants

5.5. Proposed solution method: Lagrangean relaxation and sample average approximation

The solution method used consists of lagrangean relaxation to relax the integer variable, and the sample average approximation to help run large scenarios since the GAMs commercial solver runs out memory for large scenarios involving binary variables and multi-uncertainties. Lagrangean relaxation can be used for optimization models that approximate a difficult problem of constrained optimization into simpler problem (Fisher, 1985). A solution to the relaxed

problem is an approximate solution to the original problem, and provides useful information. The reasons for adopting the Lagrangean relaxation in this problem are twofold: (1) reducing computational time since binary variables are involved and 2) since large scenarios are involved, the commercial solver is unable to solve the resulting model.

This method penalizes violations of inequality constraints using a Lagrangean multiplier, which imposes a cost on violations. Applying this method provides a flexible means of engaging the constraints from the integer variables into suitable Lagrangean multipliers which are nonnegative and nonzero, in case some inequality constraints are violated. In practice, the Lagrangean relaxed problem can be solved more easily than the original problem (Geofrion, 1974). The problem of maximizing the Lagrangean function of the dual variables (the Lagrangean multipliers) is called the Lagrangean dual problem.

As discussed earlier, Lagrangean relaxation consideration for a mixed integer linear programming problem in equation 5.37 where, $Z_p = \max cx + dy$ is the objective function and $Ax + By \leq b, Cx + Dy \leq e$ are the constraints. The terms $x \geq 0, y \geq 0$ represent the non-negative constraints.

$$\begin{aligned}
 Z_p &= \max cx + dy \\
 Ax + By &\leq b \\
 Cx + Dy &\leq e \\
 x \geq 0, y &\geq 0
 \end{aligned}
 \tag{5.37}$$

The complicating constraint is $\sum_{K \in K} \leq Y_c$, in this case is the binary constraint for biorefinery location. This is considered as the relaxed constraint and this makes it easier to solve

the resulting problem with fewer computation time or rigor in calculation. The resulting relaxed problem is written as:

$$\begin{aligned}
 Z_{PLR} &= \max cx + dy + u(b - (\sum_{K \in K} \leq Y_c)) \\
 Cx + Dy &\leq e \\
 x \geq 0, y &\geq 0
 \end{aligned}
 \tag{5.38}$$

The optimal value for this problem will be an upper bound on the initial objective function if the added $u(b - (\sum_{K \in K} \leq Y_c))$ is non-negative. Since the solution to the PLR corresponds to the upper bound, a tighter solution is needed, which is usually obtained by using the sub-gradient method by adjusting u . This corresponds to the dual which is given as:

$$\begin{aligned}
 Z_D(u) &= \min(\max_{(x, y) \in T} cx + dy + u(b - (\sum_{K \in K} \leq Y_c)), (x, y) \in T \\
 \text{Where } T &= \{x \geq 0, y \geq 0 \mid Cx + D \leq e\}
 \end{aligned}
 \tag{5.39}$$

5.5.1. Sample average approximation (SAA)

Sample average approximation (SAA) is essentially taking a sample from some fixed number of observations say, N realizations of a random vector is generated. The expected value of the function is therefore approximated or estimated by the sample average function (Ahmed and Shapiro, 2002). The obtained sample average approximation of the stochastic program is subsequently solved by a deterministic optimization algorithm, which is technically a linear or non-linear optimization. Different names such as the stochastic counterpart method and sample path optimization method are given for this method.

In this dissertation, 1000 scenarios are used. A scenario consisting of 1000 samples from uncertainty parameters such as price of raw materials, end-products, and demand data is used. Each problem is solved separately for the different uncertainties, in this case 10 different problems with 100 scenarios each. First of all the binary variables are relaxed using the lagrangean relaxation. Once the solution values are obtained, the binary decision for each 100 scenarios run is placed back into an original problem consisting of 100 scenarios and the binary variables obtained from each of the solution are now parameters. The resulting problem is solved for 1000 and 5000 scenarios in order to compare the solution found, but not much significant difference is found. The algorithm for the flow char is shown in Figure 25.

The Lagrangean relaxation in this work relaxes only the binary constraints which are assumed to be the complicating constraint. SAA on the other hand provides the flexibility of increasing the number of scenarios since the GAMS commercial solver does not have enough memory for the problem at hand. The flow charts for the lagrangean relaxation algorithm as well as the two-stage MILP are provided in the next section.

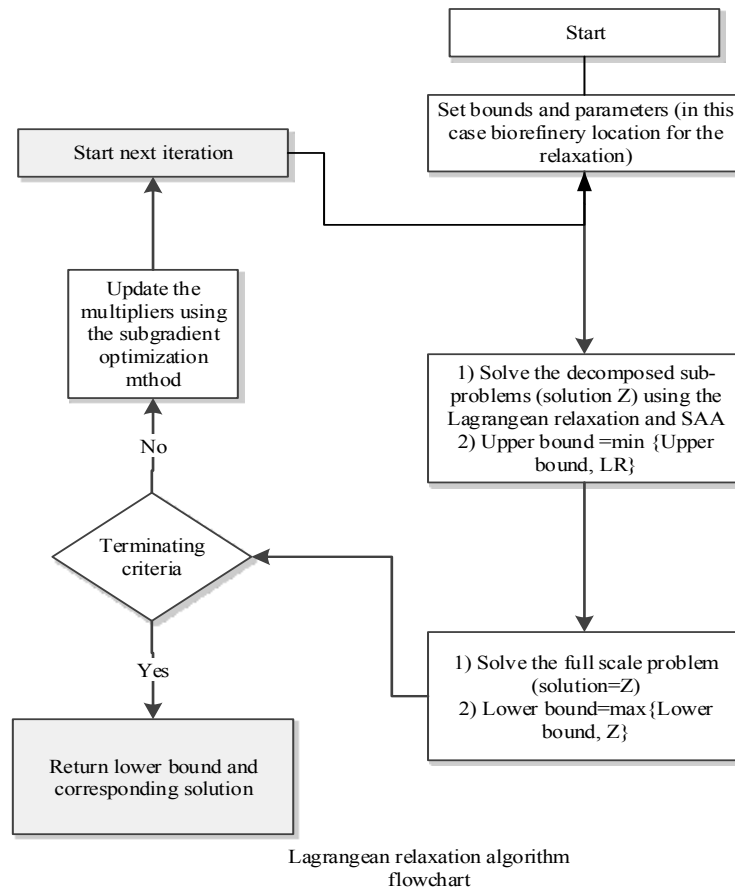


Figure 25. Flow chart of the Lagrangean Relaxation and SAA

5.6. Case study

This case study will examine an HGBSC set in North Dakota (ND) state of the U.S. ND has already established corn ethanol biorefinery plants because of the vast nature and availability of the corn and cellulosic feedstocks. Studies such as Zhang et al. (2012) have also evaluated cellulosic biofuel potential as a biomass energy crop in the Northern Great Plains (NGP) of the United States. The study also concludes that the environmental and soil conditions in the NGP are suitable for the commercial cultivation of cellulosic feedstock such as switchgrass. So the raw materials for both finished goods are well established. The case study will focus on the

combinations of these two raw materials to form an ethanol supply chain that will be able to meet the North Dakota mandate for advance ethanol consumption in 2022 by the REA.

In this problem, raw materials are purchased from three sources where each supplier transports both cellulosic and corn feedstock to the warehouse. Pre-treatment of the feedstock are carried at the warehouse and the pre-treated raw materials transported to the production facility. Four different biofuel refinery facilities convert the raw materials into end-products, two producing corn ethanol and the other two plants for cellulosic ethanol. Distances between plants and demand zones are such that, plants that have smaller distances between them and the demand zones are satisfied first.

The next section shows the case study diagram, and discusses the input parameters and results analyses.

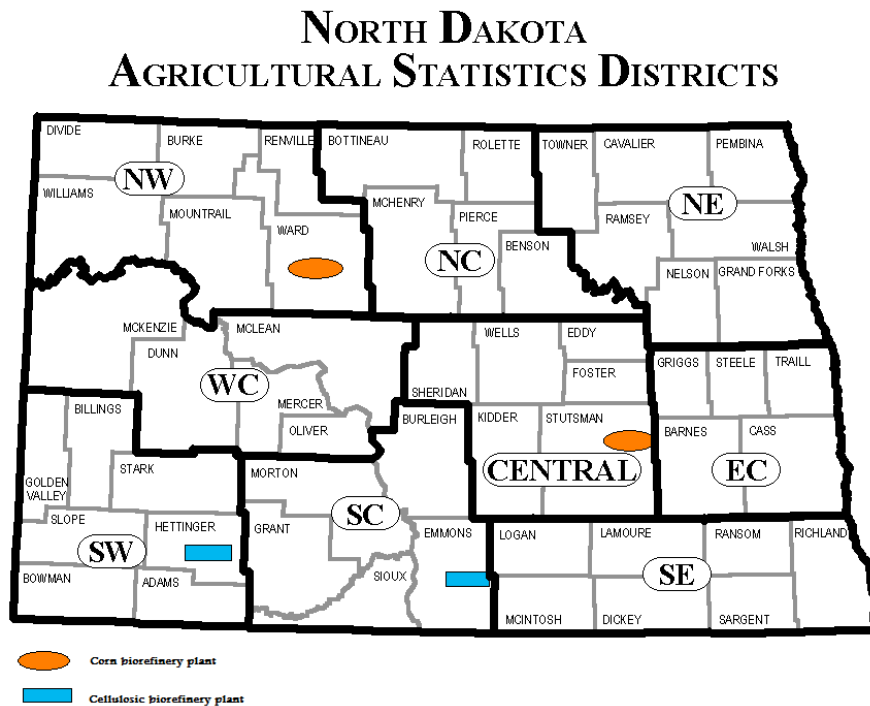


Figure 26. North Dakota agricultural districts with biorefinery plant locations

5.6.1. Input parameters

Some of the input parameters for the environmental and social sustainability are adopted from the GREET and IMPLAN databases respectively. The GREET and IMPLAN models provide detailed data information on GHG emission and social benefits of economic programs or investments. Table 17 shows a summary of the GHG emission data adapted from GREET model.

Table 17. GHG data

Carbon type	Feedstock and ethanol transportation (per mile)	Feedstock pre-treatment (per bushel)	Ethanol production (per gal)	Ethanol distribution (per gal)
CO ₂	2.1 g CO ₂ MJe	14.4 g CO ₂ MJe	28.8 g CO ₂ MJe	1.4 g CO ₂ MJe

5.6.2. Results and analysis

The model was solved by the commercial GAMS 26.3.5 version using a CPLEX solver. The model has 987 constraints, 3,149,068 continuous variables, and 4 binary variables respectively. Using a Sony Viao of Intel 1.6 Centrino processor of 2.5GHz speed, the global optimal solution was reached after approximately 4min of run time and 1.105% optimality gap. The resulting problem is solved for the 1000 scenarios and a solution of \$7.596E7 is found. In order to compare with more scenarios, 5000 additional scenarios were generated from the uncertain parameters but the solution of \$7.596E7 was obtained showing no major significance.

5.6.2.1. Results for economic and social sustainability

In this section, the economic and environmental sustainability are compared. It is found that when the economic sustainability increases, the social sustainability decreases. The economic sustainability gradually increases with an increasing level of GHG emissions as shown

in Figure 27. Social sustainability also decreases with an increasing economic value and vice versa. Figure 28 compares the economic benefits with social sustainability index. The social aspect of sustainability is provided as an index based on the IMPLAN model. This is assumed as 3.5% of the economic benefit in this case, and it is dependent on a threshold based on the level of investment (corporate social responsibility projects) the company decides. Threshold determination is a strategic level investment, which can be based on production, demand, sales, plant location, and other factors. Sensitivity analysis for the amount of sustainability contribution is conducted to realize its effect on economic and environmental sustainability. This is discussed in section 5.6.2.4. The optimal values for the proposed problem and the net economic benefits after changes in in sustainability are shown in Tables 18 and 19 respectively. For Table 19, the term CSRf refers to the CSR factor while dec and inc refers to increase and decrease in the CSR factor sensitivity analysis.

Table 18. Optimal values

Measure	Monetary amount (\$)
Economic	7.598E+07
Social	2.659E+06

Table 19. CSR analyses

Benefit	Units	CSRf dec 2 (20%)	CSRfdec 1 (10%)	Base case (0)	CSRf inc 1 (10%)	CSRf inc 2 (20%)
Economic	\$	7.601E+08	7.599E+07	7.598E+07	7.597E+07	7.593E+07

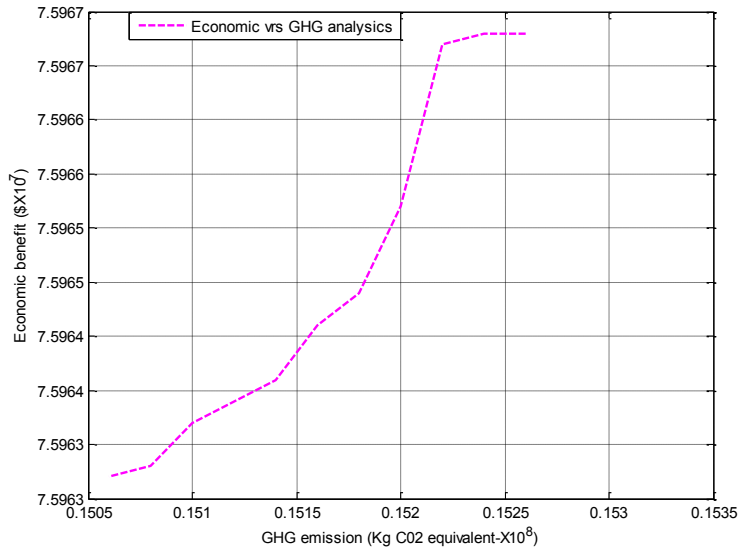


Figure 27. Showing economic and GHG sustainability

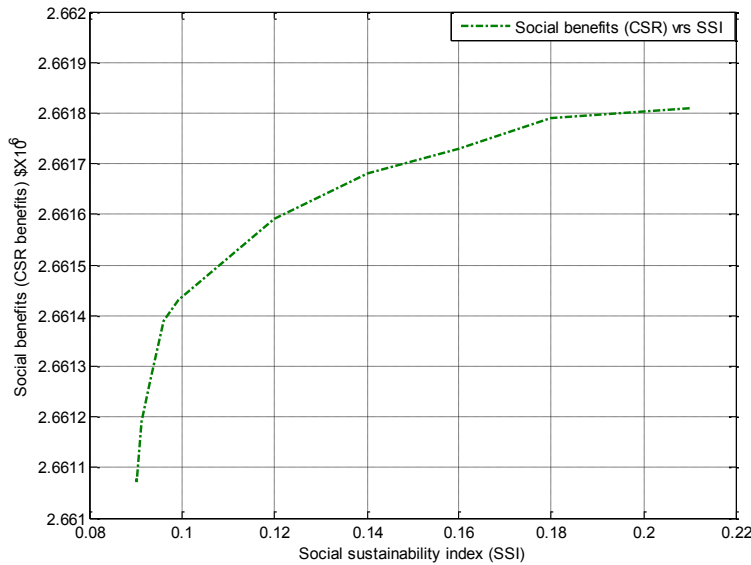


Figure 28. Showing CSR and social sustainability index

5.6.2.2. Sensitivity analysis for social and economic sustainability

Figures 29 and 30 are contour graphs that examine changes in the economic and GHG, as well as economic and social sustainability respectively. Contour 1 through 4 for economic versus GHG emission demonstrates a 5%, 10%, 15%, and 20% increment in the social sustainability.

This results in gradual decrease of the economic benefit while the GHG remains constant. The changes in the contour graph are from the impact of the analysis described by the contour relationships that the GHG emission and economic benefits, as well as the social and economic benefits have respectively. It can be concluded that gradual increase in the economic versus GHG as well as social versus economic result in corresponding changes in the contour graphs. It is observed that when the social sustainability increases up to a certain level, the economic values also increase by the corresponding gradients or values for the contour. The same is observed when the GHG and economic benefits contour is analyzed. The increase in GHG value results in an increase in the economic model.

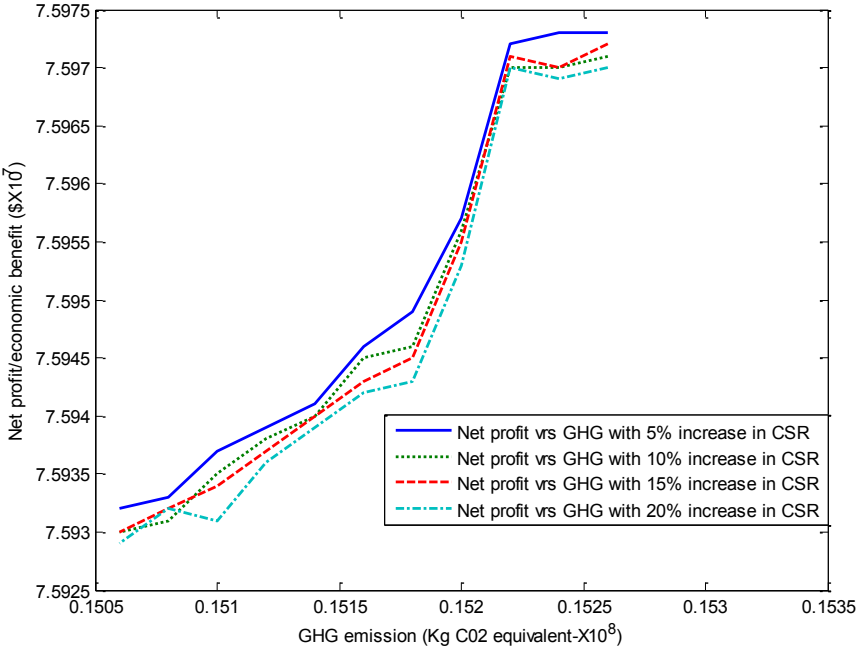


Figure 29. Contour graph for economic and GHG sustainability

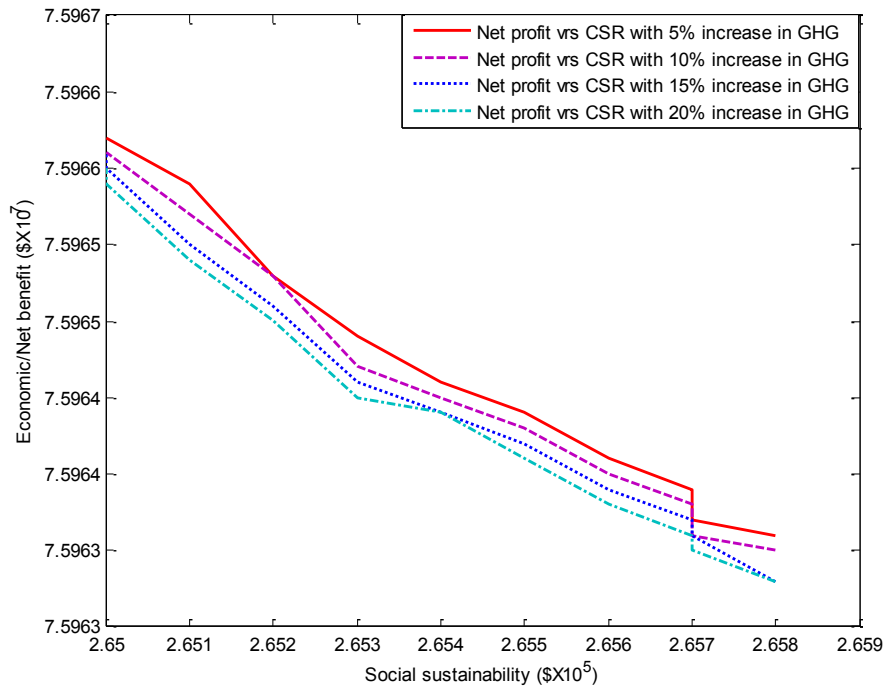


Figure 30. Contour graph for economic and social sustainability

5.6.2.3. Sensitivity analysis for social sustainability changes

From the study, the number of hospitals, schools, and community centers from the optimal solution are 6, 4 and 3 respectively. A further analysis is conducted by holding the number of schools and community centers constant, and increasing the number of hospitals. This is shown in Figure 31. The resulting model is then solved. The results indicate that the number of hospitals can be increased from 6 to 8 and the threshold for corporate social responsibility is reached. This means investing in the number of hospitals contribute a larger share in the corporate social sustainability. Meaning, a biorefinery producing plant should access what kinds of corporate responsibility projects to invest in, having in mind how much each contributes to the overall corporate level investment. Meanwhile, similar analyses can be considered for the number of schools and community centers as well.

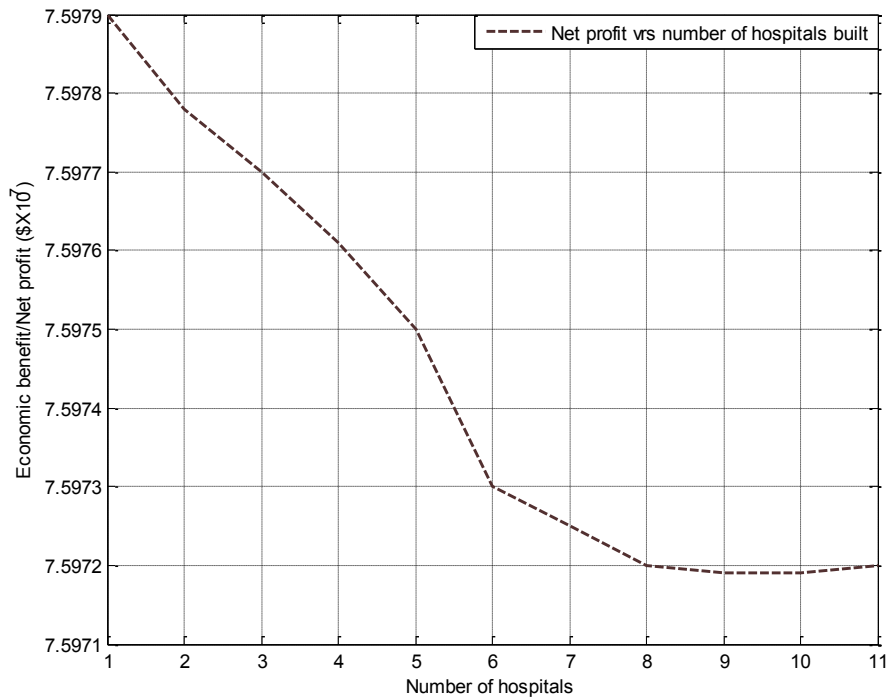


Figure 31. Graph for economic sustainability and number of hospitals

5.6.2.4. Managerial insight for economic versus social benefits

As discussed previously, the economic benefit reduces as the social sustainability increases until the threshold for the investment of social sustainability, that is \$2.659E6 is reached. Accordingly, an investment of \$2.659E6 results in an economic net benefit decrease of \$7.596E7. This means if further increase in social benefit is needed, then a strategic decision would have to be made. In this case, an increase in profit while maintaining the same social benefit will mean increasing biorefinery capacity as well as high demand realization. Also, a decision at an economic benefit of \$7.5967E7, corresponds to a social sustainability benefit of \$2.6591E6, as compared to an economic benefit of \$7.5966E7 with a social sustainability benefit of \$2.6593E6. This means a biorefinery investment of \$2.6593E6 for a social sustainability is feasible for an economic value of \$7.5966E7. Meanwhile, the net economic benefit of \$7.5966E7 means sustainable project limit is reached. Similarly, the results also indicate the

location for the biorefinery will not be affected if the minimum economic benefit is to remain approximately \$7.5966E7.

Further analysis is conducted for the GHG emission and economic benefit. The results indicate that after carbon emissions of 0.155E8 kg C02 equivalent, the maximum economic benefit that can be achieved is around \$7.5967E7 as illustrated. This means further production can result in more emission, but the limit on the profit maximization or economic benefit will have to be set at a different target. Expanding capacity for more production should also be compensated for more profit margins if there is unlimited demand, which is not practical in most cases since demand has limit. All these analyses can be referenced from Figures 32 and 33.

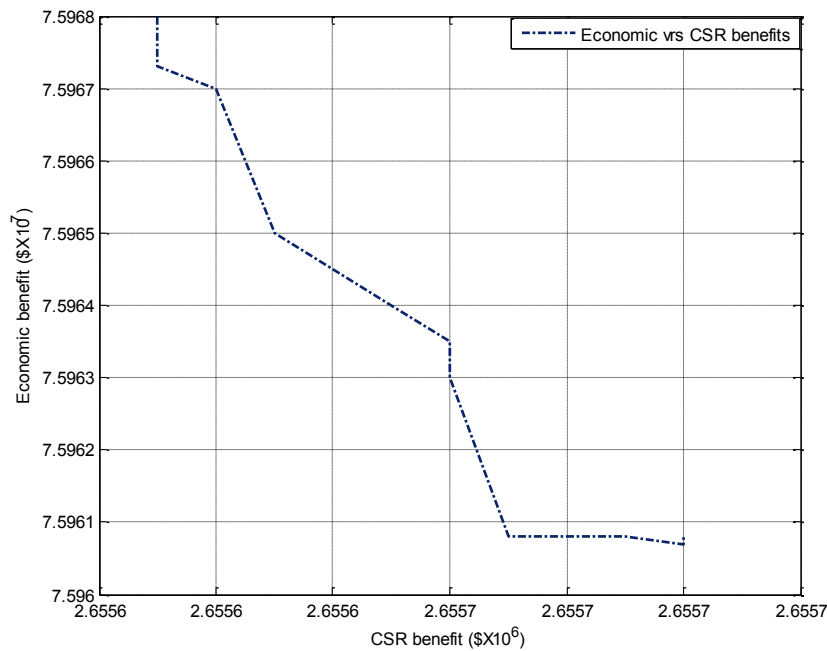


Figure 32. Managerial insight graph for social and economic sustainability

5.7. Conclusion and future research

This section of the dissertation considers supply chain sustainability by incorporating all the three sustainability concepts, i.e. economic, environmental, and social. The model considers economic sustainability in the supply chain maximization of profit, while the environmental and

social aspects adopt the GHG emission minimization, and CSR maximization respectively. Cost of corn and cellulosic feedstock are random and follow Mean Reversion (MR) model. A two-stage stochastic mixed integer linear programming approach is used, where the first-stage decisions consist of the biorefinery location, capacity of warehouse, and capacity of biorefinery plants. The second-stage decisions consist of corn and cellulosic feedstock to purchase, amount of feedstock to pre-treat, amount of ethanol produced, amount of ethanol sold, and the amount of co-products to produce and sell. The resulting model is solved using the Lagrangean Relaxation and SAA. Analyses of the results indicate incorporating sustainability concepts into the model provide managed expectations of profit. Also, sensitivity analyses based on GHG emission and the economic benefits are conducted as well social and economic benefits. The results conclude that increasing social sustainability will decrease economic benefits unless there is a threshold for social sustainability. Additionally, the more the GHG emission, the more the economic benefit till plant capacity to produce the sale amount of ethanol is met. Further sensitivity analyses are conducted for managerial insights.

Future research directions will be to extend the model to include inventory and spatial representation of the supply chain. The temporal model developed in this work should be compared to spatial model to make informed decisions. Time, or temporal, concerns about demand levels are common in forecasting and can impact the supply chain profitability. Demand variation relative to time can result in a gradual decrease in profit, especially if seasonality factors are incorporated. This can result in another research mostly developing forecasting models for demand in a supply chain setting, where time series models can be used.

Multi-stage stochastic programming with inventory will be another future work that will be worth considering. Since inventory management can affect the entire the supply chain profit realization, especially at the multi-stage inventory level.

Additional consideration is logistics, which has space and time dimensions, will help in allocating demand at the spatial level which is needed to plan biorefinery and warehouse locations. Meanwhile, inventory can be balanced across the logistics network, and geographically allocate transportation resources. In addition, forecasting techniques can be selected to reflect geographic differences as it can affect demand patterns. A further future study will be to use different forecasting techniques that may differ based on whether demand is forecasted, aggregated or disaggregated by geographic locations.

Additional future research directions are incorporating uncertainty in the GHG permit purchasing and developing a model that is based on carbon trading, that is purchasing and selling carbon permits in an uncertain environment. Another research direction is using futures and options to hedge against the number of permits to purchase or sell, since uncertainties in biofuel demand affect the number of permits needed.

CHAPTER 6: CONCLUSION AND FUTURE RESEARCH

6.1. Conclusion and future work

This chapter of the dissertation is a summary of the findings and contributions in this dissertation. Also, some meaningful research directions are provided for possible future research.

6.2. Conclusions

Renewable energy, which includes ethanol, is becoming one of the world's fastest growing sources of clean and renewable energy in the transportation sector. Therefore the supply chain which considers the purchasing of raw material through the production of ethanol to distribution is critical to the entire value chain.

Integration of uncertainties, hedging methods, and sustainability concepts into the biofuel supply chain is crucial. This is highly related to strategic, tactical, and operational biofuel supply chain decisions. Accurately incorporation uncertainties and hedging against these uncertainties is extremely important. Therefore, adaptive and reliable modeling methods that help in addressing these issues are taken into consideration. Meanwhile, with the ongoing ethanol markets involving trading futures in both corn feedstock and ethanol are expected to directly trade other output such as Renewable Identification Numbers (RINs) in the energy markets. Another issue of particular importance for biofuel production plants is how to maximize its net earnings by optimizing the hedging strategies in the gradually fledgling commodity trading market for ethanol. However, the existing research efforts towards the issues raised have attracted much attention in research but still need new and novel contribution as this work addresses. This literature gap has directly stimulated this dissertation research direction. The research tasks conducted in this dissertation study, in addition to the corresponding findings and contributions, as well as future research directions are summarized below.

First, a provision of the general overview of the background and structure of the biofuel supply chain is considered. Also, a literature of the decision making process, and the uncertainties in the supply chain are provided. Subsequently, methodologies that have been applied in other supply chain to handle uncertainties are implemented. Finally, sustainability concepts and models are discussed.

Secondly, the next section developed a stochastic linear programming model for the production planning of a multi-product biofuel supply chain. Demands of end products follow normal distributions with known mean and standard deviation, and Geometric Brownian Motions (GBMs) are used to model the price uncertainties of end products. A bender's decomposition with Monte Carlo simulation algorithm is applied to solve the proposed model.

The case study is based on a biofuel supply chain in North Dakota. The results of proposed stochastic model outperform the results of deterministic model based on the simulation analyses. Sensitivity analyses are performed to gain management insight regarding the uncertainties.

The third section of the dissertation develops a model that uses hedging strategies in a hybrid generation biofuel supply chain (HGBSC) setting. The hedging method considers the futures and spot prices of corn and cellulosic feedstocks respectively, while the ethanol end-products are hedged using futures. Non-hedging strategy uses spot prices for the purchase of feedstock and sale of end-products. A two-stage stochastic linear programming method based on the Multi-cut Benders Decomposition Algorithm is used to solve the resulting model. The analyses show differences in profit margins in relation to hedging and non-hedging with the non-hedging being less than the hedging. Also, the profit values for the non-hedging at lower profits are observed to be more risky as compared to the profit values of the hedged decisions.

Finally, supply chain sustainability modeling by incorporating all the three sustainability concepts, i.e. economic, environmental, and social are implemented. The model considers economic sustainability for the supply chain maximization of profit, while the environmental and social aspect adopts the GHG emission and CSR respectively. Cost of corn and cellulosic feedstock are random and follow Mean Reversion (MR) model. A two-stage stochastic mixed integer linear programming approach is used, where the first-stage decisions consider biorefinery locations including warehouse. The resulting model is solved using the LR with sub-gradient method and the SAA. Analyses of the results indicate incorporating sustainability concepts into the model provide managed expectations of profit. Also the effects between economic and social, as well as the economic and GHG are examined.

6.3. Future work

Modeling uncertainty in the biofuel supply chain can be achieved by using either scenario or distribution based approaches. In the scenario based approach, the uncertainty can be described by a set of discrete scenarios, capturing future uncertainty. Each scenario can be associated with a probability level representing the decision maker's expectation of the occurrence of a particular scenario. The distribution based scheme can be used when a set of discrete scenarios cannot be identified, and only a continuous range of potential figures can be predicted. Incorporating these processes in modeling biofuel supply chain uncertainties might be useful in obtaining optimal decision. As for the issues on risk hedging and sustainability, the following directions and areas are of high interest and importance:

- Applying other solution methods should be explored in considering these uncertainties. Methodologies such as analytical, simulation and other hybrid methods can be utilized in solving biofuel supply chain problems with uncertainties. Some hedging strategies need to be considered

to hedge the risks in biofuel supply chain. The risks include risks from feedstock supply and price, oil price shocks, and other forms of risks within and outside the biofuel supply chain. Applying operational and financial hedging tools will be a potential research direction.

- The proposed model can be applied in any biomass based biofuel supply chain. In order to establish a robust biofuel supply chain, more issues should be considered in the future research. Therefore, the extension of the research will be focused on 1) considering more uncertainties, such as uncertainties of raw materials supply, production, and transportation, in the model 2) incorporating disruptions, such as disruptions of raw material supply and demands, in the model and 3) considering the sustainability concepts and including environmental and social performance measurements in the model.

- Future research can consider where financial and operational decisions are made and reviewed, daily, weekly, or monthly which will reflect real time operation. Other future considerations will be adopting operational hedging based on inventory control, multiple suppliers, supply contracts, and lead time variability. Finally, additional uncertainties such as conversion rate might influence the optimal hedging strategies that will be used. Combination of hedging strategies such as future, options, and futures options will be a good research direction.

- Final future research directions are incorporating uncertainty in the GHG permit purchasing and selling in a multi-stage setting. Another research direction is using futures and options to hedge against the number of permits to purchase or sell, since uncertainties in biofuel demand affect the number of permits needed.

- Spatial supply chain optimization: The methods considered in this work are mainly from the temporal supply chain perspective. A future consideration for this work is the

incorporation of spatial supply chain where logistics, demand forecasting, GIS methods and LP algorithms can be used to determine the spatial effect on the supply chain.

- Most of the time period in this work considered a two-stage stochastic case. A further extension for multi-stage stochastic linear and non-linear problems will be a good research direction since multi-stage will have an impact on the production, inventory and other decision variables in the supply chain.

- Hybrid algorithms that involve the use of Benders decomposition, Multi-cut Benders decomposition, Lagrangean relaxation and Sample Average Approximation should be used to determine their impacts on the solution figure, iteration number, and the computational times.

- Risk management that involves hedging strategies like options and futures-options can provide further insight into the risk management strategies that can be adopted. Incorporating these risks and integrating with a new output variable, RINS will be a good future research area. RINS are currently expected to be traded in the near future. This will provide an added insight into the ethanol supply chain from the blender's perspective.

- A very important concept that can help in the risk management analyses is using copula. Copula is able to provide or describe the relationship between or among input and output variables such as corn, ethanol, DDGS and corn oil. Copula helps to define a certain dependence structure and provide information on the correlation of the variables. Risk management using copulas with Value at Risk (VaR) will be a good future research direction.

- Uncertainties in volume of feedstock will also be essential for further research direction. An instance is the North Dakota and US drought in 2012 which affected the volumes of corn production. This means a seasonality effect can be added to the model to provide further perspectives.

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