Sustainable Petroleum Supply Chains Created in Response to the US Government Policies

DAVOUD GHAHREMANLOU

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A Thesis submitted to the School of Graduate Studies in partial fulfillment
of the requirements for the degree of **Doctor of Philosophy**.

Faculty of Business Administration

Memorial University of Newfoundland

November 2020

St. John's Newfoundland

Abstract

Socialization and long-distance trading began after the basic needs of early people were met. Millennia later, the 'modern' discovery of crude oil (or petroleum) and the development of the internal combustion engine resulted in improvements in transportation, chiefly in terms of increasing speed. Steam engines were quickly replaced by these new engines, used to power ships and trains. The revolution of the combustion engine – and the new utilization of petroleum with which it is fueled – marked the beginning of a new age in global transportation and industry. The invention of the automobile, utilizing this internal combustion engine, and the advent of its mass production at the beginning of the 20^{th} century served as yet another turning point in transportation history. Currently, land transportation using gasoline derived from crude oil is the most popular mode of transportation. However, the destructive impact of gasoline on the environment, as well as the imbalance in the distribution of oil reservoirs among countries, led governments to explore some alternate fuel sources.

Legislation converting Conventional Petroleum Supply Chains (CPSCs)[1] to Sustainable Petroleum Supply Chains (SPSCs)[2], seemed to offer the best solution for addressing environmental concerns and energy security. For this purpose, the United States, the world's largest oil consumer, has created policies to make SPSCs. These policies aimed to support production and consumption of bioethanol[3] as a gasoline additive, resulting in the creation of Bioethanol Supply Chains[4] and merging them with CPSCs to form SPSCs. Though these new regulations have created new opportunities, they also added new burdens to the

[1] also called Conventional Crude Oil Supply Chains (CCOSCs)
[2] also referred to as Sustainable Crude Oil Supply Chains (SCOSCs)
[3] also called ethanol
[4] also called Ethanol Supply Chains

obligated parties for compliance. Thus, as the leader of SPSCs, the US government ought to determine how the policies influence SPSCs in different financial risk conditions, before enacting them. This evaluation would assist the US government to make decisions within a sustainable framework, the significance of which is well recognized. This results in enhancement of business confidence through guaranteed investment security and profitability. On the other hand, the investors would focus on making robust strategic decisions against policy changes, and resilient strategic decisions devised to stand up to risk averse situations, like the current one created by Coronavirus Disease (COVID-19) and the 2020 Saudi Arabia-Russia Oil Price War.

This thesis aims to support the government and investors in this regard by running computational experiments. To that end, we have carried out studies resulting in the following six papers:

1. Ghahremanlou, D. and W. Kubiak (2020a). Impact of government policies on Sustainable Petroleum Supply Chain (SPSC): A case study - Part I (Models). *Decision Making in Manufacturing and Services*. In Press.

2. Ghahremanlou, D. and W. Kubiak (2020b). Impact of government policies on Sustainable Petroleum Supply Chain (SPSC): A case study - Part II (The State of Nebraska). *Decision Making in Manufacturing and Services*. In Press.

3. Ghahremanlou, D. and W. Kubiak (2020c). Sustainable Petroleum Supply Chains created during economic crisis in response to US government policies. *International Journal of Sustainable Economy*. Submitted.

4. Ghahremanlou, D. and W. Kubiak (2020d). An approach to studying Sustainable Crude Oil Supply Chains (SCOSCs) evolved by changing US government policies - Part I (Models). *Journal of Cleaner Production*. Submitted.

5. Ghahremanlou, D. and W. Kubiak (2020e). An approach to studying Sustainable Crude Oil Supply Chains (SCOSCs) evolved by changing US government policies - Part II (Case Study). *Journal of Cleaner Production*. Submitted.

6. Ghahremanlou, D. and W. Kubiak (2020f). US Sustainable Crude Oil Supply Chains (SCOSCs) during economic crises. To be submitted.

These papers form Chapters 2 – 7 of this thesis, respectively. The three papers focusing on creating the most environmentally friendly SPSC which can be applied in 23 states that currently do not have any bio-refinery in place with minimum challenges, make up Chapters 2 – 4. The other three papers dealing with the SPSC in the 27 states with already existing facilities create Chapters 5 – 7. This thesis also includes two more chapters, the Introduction, Chapter 1, and Conclusions, Chapter 8. The former provides detailed information about what to expect in this thesis and why; the latter summarizes the findings of the thesis.
In Chapter 2, we develop a two-stage stochastic programming model, called General Model (GM), for the evolution of the SPSC. The model accounts for 2^{nd} generation bioethanol, the most environmentally friendly bioethanol developed so far. However, since the GM, like any other GMs in the literature, is NP-hard in the strong sense, we develop a Lean Model (LM). Then we prove relationships between solutions to the GM and solutions to the LM. We employ the LM to run a computational experiment, including 22,050 policy scenarios, in Chapter 3. Chapter 4 converts the risk neutral model in paper one to a risk averse model, often appropriate during economic crises, by applying Conditional Value-at-Risk (CVaR); then we conduct a case study. Chapter 5 extends the model in paper one, by including all existing infrastructures, 1^{st} and 2^{nd} generation bioethanol, currently the only commercial ones, and their imports and exports. We propose the Extended General Model (EGM), derive the Extended Lean Model (ELM), and prove the relationships between them. The ELM is applied to run a computational experiment with 21,420 alternative policy scenarios,

in Chapter 6. We employ the CVaR and change the risk neutral model in paper four to a risk averse model and perform a case study, in Chapter 7. Note that the reason for a different number of policy scenarios in Chapters 3 and 4 relative to Chapters 6 and 7 is the cheaper price of the 1^{st} generation bioethanol as compared to 2^{nd} generation, see Sections 3.3 and 6.3. Given the significance of the economic, environmental, and social aspects of the SPSC, all the case study results, more particularly policy impacts and policy recommendations, in Chapters 3, 4, 6, and 7, are provided within the framework of sustainability; robust strategic investment decisions despite inevitable policy changes are also provided. In Chapters 4 and 7 the results of their risk averse models are respectively compared with their corresponding risk neutral models in Chapters 3 and 6, to further highlight their significance and provide resilient strategic investment decisions in times of financial risk change.

Acknowledgements

My foremost gratitude to Prof. Wieslaw Kubiak, my advisor, for his support and guidance during my PhD program. It has been an honour to work with him and learn from him. Also, I am sincerely grateful to my multidisciplinary supervisory Committee, Drs. David Tulett and Kelly Hawboldt, for their time assignment and insightful comments. This made the study smoother and greatly enhanced the quality. I extend my appreciation to other faculty members at Memorial University of Newfoundland, more particularly Drs. Yuyue (Peter) Song and Ginger Ke, for elaborating on the relevant topics on their areas of proficiency.

My special thanks to Dean of Faculty of Business Administration at Memorial University of Newfoundland, Dr. Isabelle Dostaler, for sharing her invaluable experience and providing support. I am also thankful to Drs. Rachelle Shannahan and Travor Brown, the current and former PhD Program Directors, respectively. Research funding from Natural Sciences and Engineering Research Council of Canada (NSERC), BMO Financial Group, Faculty of Business Administration and School of Graduate Studies at Memorial University of Newfoundland are deeply acknowledged.

This research is dedicated to my parents, Ezzatollah Ghahremanlou and Nahid Saadati, their love, support and sacrifices have enabled me to pursue my PhD degree. My final thanks to my dear brothers, Amir and Ali, for their encouragements.

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Chapter 1

Introduction

Sun is the world's main source of energy. Different types of vehicles use different kinds of fuels, which are derived directly or indirectly from the sun's energy. The majority of the vehicles currently available in the global market take their energy from gasoline and diesel derived from fossil fuels, more precisely crude oil (also called petroleum), which are not sustainable. Gasoline derived from petroleum, sometimes called petroleum gasoline, makes up more than half of the transportation fuels in the US, the largest global petroleum producer and consumer. However, energy independency and global warming, one of the biggest challenges facing humanity in the current century, have forced the US government to make new policies, leading to sustainable energy. Although the US fuel market restrictions and compatibility of existing infrastructure have not yet permitted complete replacement of petroleum gasoline with new sustainable fuels, the policies supported consumption and production of bioethanol from biological materials, e.g., corn and corn stover, as an additive to petroleum gasoline. In other words, the policies created and merged Bioethanol Supply Chains (BSCs) with Conventional Petroleum Supply Chains (CPSCs) and formed Sustainable Petroleum Supply Chains (SPSCs). The significance of studying SPSCs during different economic conditions, to find out how policies enable them to meet government objectives within sustainability framework (economic, environmental, and social perspectives), has received a great deal of emphasis in the literature by policy-makers and industry; however, there is no appropriate study to address this gap. Therefore, this thesis aims to fill this gap by conducting computational experiments.

This thesis includes eight Chapters. The introduction to the thesis, Chapter 1, includes seven main sections: Sections 1.1 and 1.2 cover the fundamentals and history of energy; Section 1.3 explains transportation, its modes, and fuels; it also clarifies the reasons for transition from fossil fuels to renewable fuels. The role of policies in fuel transition is discussed in Section 1.4, with a focus on US policies; Section 1.5 examines the literature and presents the research gaps that are addressed by this thesis; Section 1.6 discusses the appropriate modeling and solution approach for the thesis; finally, Section 1.7 summarizes our contributions and outlines the details in the coming seven chapters.

1.1 Basic Concepts

1.1.1 Energy Etymology and Definition

The word *energy* originated with Aristotle, in his explanation of *potentiality* and *actuality* in Nicomachean Ethics. Potentiality, which is referred to as *dunamis* in Ancient Greek and written $\delta\acute{\upsilon}\nu\alpha\mu\iota\varsigma$, is the ability to be. In contrast, Aristotle uses *energeia* ($\dot{\varepsilon}\nu\acute{\varepsilon}\rho\gamma\varepsilon\iota\alpha$) and *entelecheia* ($\dot{\varepsilon}\nu\tau\varepsilon\lambda\acute{\varepsilon}\chi\varepsilon\iota\alpha$) interchangeably for actuality, which is an action that passes something from possibility to complete reality. The word $\dot{\varepsilon}\nu\acute{\varepsilon}\rho\gamma\varepsilon\iota\alpha$ is made of $\varepsilon\nu$ and $\acute{\varepsilon}\rho\gamma o\nu$, which mean“in” and “work” respectively. According to Aristotle, anything’s existence is maintained by $\dot{\varepsilon}\nu\acute{\varepsilon}\rho\gamma\varepsilon\iota\alpha$. Therefore, energeia was coined to ascribe change, work, action and motion (Smil 2017a; Menn 1994).

From the 17^{th} century to the first decade of the 19^{th} century significant theoretical energy studies were implemented which gave a better understanding of energy. Isaac Newton's research and James Watt's work on steam engines offered further clarification. Later, Sadi Carnot, a French engineer, wrote down the principles for generating kinetic energy from heat (Smil 2017a). Julius Robert Mayer discovered that heat and work are one and the same and can be converted to each other in specific proportions. Based on this, he created the law of the conservation of energy and subsequently extended it to all natural phenomena (Caneva 2015). Along this line, in 1847, James Prescott Joule ran accurate experiments for calculating the rate of conversion of heat to kinetic energy. The law of the conservation of energy is currently known as the first law of thermodynamics. In 1865, Rudolf Clausius, coined the word *entropy*, meaning transformation, to show the degree of disorder in a closed system. He formulated the second law of thermodynamics, which is that the entropy of a closed system is not decreasing. However, the earth's biosphere does not follow the second law of thermodynamics, as solar energy is converted into plant mass by photosynthesis, resulting in greater order as it is a closed system. Following this, in 1906, Walther Nernst formulated the third law, at absolute zero ($-273°C$) entropy tends to not change as all processes stop (Smil 2017a). However, a year before this Albert Einstein came up with $E = mc^2$ proving that mass is a form of energy; m and c are mass and the speed of light respectively. As an example, nuclear reactors convert a mass of uranium to energy (Bodanis 2005). Although there have been efforts made toward realizing the concept of energy, it seems to become more intellectually elusive. Richard Feynmen, a well-known physicist, in his 1963 lectures says:

> It is important to realize that in physics today, we have no knowledge of what energy is. We do not have a picture that energy comes in little blobs of a definite amount. It is not that way. However, there are formulas for calculating some numerical quantity, ... It is an abstract thing in that it does not tell us the mechanism or the reasons for the various formulas (Feynman et al. 1965).

However, energy is commonly defined as “the capacity for doing work”. Some derivatives of the word are the verb *energize* and the adjective *energetic* (Smil 2017a).

1.1.2 Energy Types, Conversion, and Units

There are different kinds of energies which are converted to each other, see Smil (2017a). For instance, electromagnetic energy is converted to chemical energy in plants by photosynthesis (This is a highly inefficient conversion). Then, this chemical energy in plants could be converted to fuel, including another type of chemical energy, by a bio-refinery. After that, fuel is combusted to produce thermal energy, which creates momentum in a vehicle’s engine allowing movements.

Two main sources of chemical energy are:

1. Biomass, which is the organic material in plants and animals;

2. Fossil fuels, which are formed from dead biomass.

The chemical energy is held in the atomic bonds and released in the form of heat by rapid oxidation called *combustion*. This process generates some pollutants i.e. carbon dioxide and sulfur oxide (Smil 2017a).

To find the unit for energy, one needs to consider its definition, which is the capacity to do work. Also, the amount of energy can be calculated by having the amount of force, F, required by an object to move over a distance, d. According to Newton’s second law of motion the unit for F is $\frac{kg \cdot m}{s^2}$, which is called a *Newton* (N). Therefore, the unit for energy, E, will be $\frac{kg \cdot m^2}{s^2}$, this is referred to as a *joule* (J). The aforementioned units are based on the International System of Units (SI). Some people still use the traditional counterparts, e.g. instead of joule, British thermal unit (Btu); 1 $Btu = 1055$ J (Halliday et al. 2013).

Energy content of fuels	MJ/kg
Hydrogen	114.0
Gasolines	44.0–45.0
Crude oils	42.0–44.0
Natural gas	33.0–37.0
Anthracite	29.0–31.0
Bituminous coal	22.0–26.0
Lignites	12.0–20.0
Air-dried wood	14.0–16.0
Cereal straws	12.0–15.0

Table 1.1: Energy Content of Fuels (Smil 2017a)

1.2 Energy Sources and History

The sun is the main source of energy for the maintenance of life. The sun's radiation, or electromagnetic radiation, carries the energy created during nuclear fusion and chemical reactions occurring within the sun (Smil 2017a).

Each planet receives the sun's rays, but thus far life has not been observed on any planet apart from the Earth. The earth's energy budget is partitioned by different substances. The sun's energy is absorbed by gases in the atmosphere as it passes through, and is transformed to heat. Some of the heat is absorbed by the Earth, and the rest is reflected back into the atmosphere. The atmosphere acts as a greenhouse, trapping the heat to maintain the earth's temperature, making conditions suitable for life; this is referred to as the *greenhouse effect* (Solomon et al. 2011; Begon et al. 2006).

Initially humans were hunter-gatherers. Gathering, hunting, consuming and shelter creation require muscular energy. This energy came directly or indirectly from starch through photosynthesis. Fishing near a coastline provided a high positive energy return, so it was natural the earliest communities grew up near water. Early agriculture initially followed along the Nile and in Northern China along the Yilou River valley (Smil 2017a).

Biomass was burnt to generate heat and light. The source of biomass was mainly agriculture residues and forest. However, the forest could not always be a sustainable source. Interior burning of biomass also created some carbon monoxide, which is toxic to humans. Thus, better stoves with more efficient venting were created. Lighting was provided by torches fueled with animal and plant fats. The need for efficiency ushered in the use of gas derived from coal and kerosene derived from crude oil, and eventually incandescent light bulbs (Smil 2017a).

1.3 Transportation and Fuels

1.3.1 Transportation History and Modes

With basic needs met and with a surplus of energy, people organized into a more permanent social structure. Beginning as tribes to eventually more sophisticated cities such as Rome with over half million and Baghdad with 700,000 inhabitants. Along with urbanization came codification of law, economic rules, religion, and science. Transportation was required for the movement of goods and people as urban areas expanded and trade between cities increased. Wheeled transport developed quite slowly due to road and vehicle design. Wind-powered ships proved to be inefficient by the 18^{th} century. Later, Europeans made better ships, thus improving their abilities to trade with other countries. Industrialization beginning in the 18^{th} century improved transportation drastically. Scientists working with gases invented hot air balloons during the 18^{th} century. After 1840, rail transportation emerged. In the late 19^{th} and early 20^{th} centuries, the use of internal combustion and electric engines expanded. In the early 20th century, aircraft were developed, and their design quickly progressing throughout the century. After the war, better commercial airplanes were manufactured (Smil 2017a).

Transportation modes (transportation means) can be categorized into three main classes (Chopra and Meindl 2001):

1. Land- this consists of road and rail, the latter being more economical as it does not provide the door-to-door transportation and it allows a greater volume of goods in less time.

2. Water- this mode is limited by accessibility to water. It allows the transport of a large volume of goods at a lower cost.

3. Air- this mode of transportation is the fastest route of shipment, but the most expensive. Cargo may be shipped by this mode, but most products have low volume and are shipped using this mean due to required expediency.

1.3.2 Land Transportation and Transition in Fuels

Land transportation, the most popular mode of transportation in the world, utilizes gasoline, diesel, etc. Gasoline and diesel, derived from fossil fuels, have been the main sources of this transportation mode for several decades. Gasoline is in greater demand than diesel (Dahl 2012; Demirbas 2008; Kreith and Krumdieck 2013).

In the past few decades, researchers have attempted to introduce new transportation fuels, e.g. bioethanol, an additive and/or replacement for gasoline, in order to reduce dependency upon crude oil. These efforts have been supported by some governments. Use of alternative fuel sources has been stimulated for the following reasons:

1. Reservoirs of crude oil are unevenly distributed globally. Almost 50% of oil reservoirs are located in the Middle East, see Figure 1.1 (Rempel 2011; BP Statistical Review of World Energy 2016). This region includes the countries which have been experiencing political fluctuations for decades (World Economic Forum 2016; Agarwal 2007), thus greatly impacting oil price (Yan 2012; International Monetary Fund 2016).

2. Oil consumption rate is higher than the rate of production. It is estimated that many oil reservoirs may only last for 41 years (Agarwal 2007), hence it is called a non-renewable energy.

3. Consumption of petroleum fuels releases environmental pollutants, which accelerate global warming, and are detrimental to human health. Climate change resulting from global warming is unbalancing the earth's energy cycle through the emission of Greenhouse Gases (GHGs), which allow higher energy waves to enter the atmosphere and prevent low energy waves from leaving. This leads to a rise in the world temperature, resulting in: desert expansion, sea level rise, extreme weather, food insecurity, ocean acidification, species extinction, etc. The main GHGs are CO_2, CH_4, and N_2O. Almost 78% of CO_2 is generated by fossil fuels consumption (transportation emission contributes about 23% (Di Lullo et al. 2016)) (Pearson 2011; Wirth 1989a). Furthermore, other pollutants, e.g. carbon monoxide (CO) and nitrogen oxides (NO_x) lead to heart disorders and irritation of respiratory organs respectively (Hosseinpoor et al. 2005; Colvile et al. 2002; Santos 2017; Martonen and Schroeter 2003a;b).

The aforementioned reasons motivated governments to seek more sustainable sources of energy for transportation, especially land transportation. However, to secure collaboration of all parties, e.g. business and academia, international and national legislation were

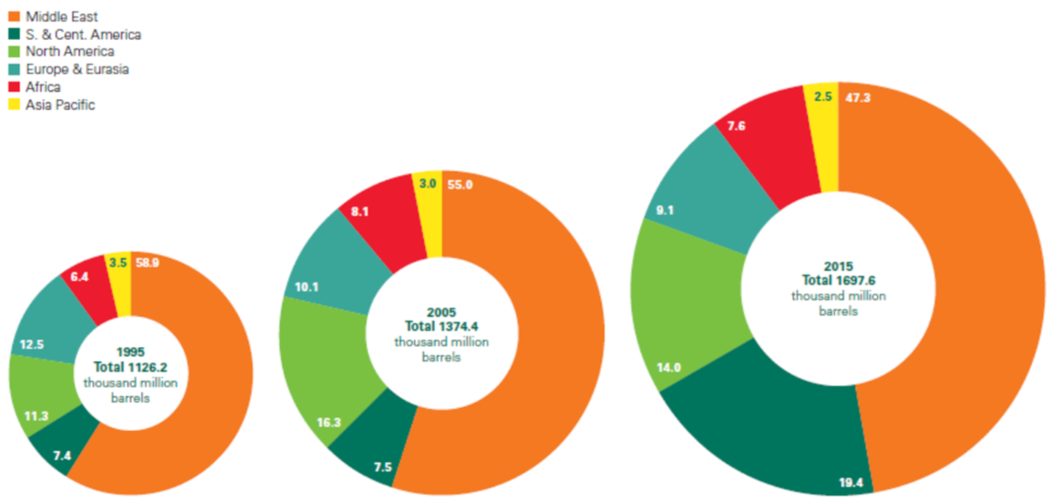


Figure 1.1: Distribution of proven reserves in 1995, 2005 and 2015 (Percentage) (BP Statistical Review of World Energy 2016)

developed (Huang et al. 2009; El-Naggar et al. 2014; Humbird et al. 2011).

1.3.3 Fossil Fuels

Fossil fuels are generated from dead organisms, preserved in the Earth's crust; approximately, for producing one gram of fossil fuel carbon seven kilograms of accumulated carbon in organic matter are needed (Schobert 2013). These organisms begin decaying, and the process continues until reaches about 98% completion. This takes millions of years to create fossil fuels. Fossil fuels are non-renewable and unsustainable, since their rate of consumption vastly exceeds the production rate (Panchal Mehulkumar and Dwivedi 2013). Fossil fuels formation is complicated, laboratory production is currently unfeasible, as for each chemical reaction we need exact reactants, conditions (pressure, time, temperature, and catalysis), and SOP (standard operation procedure) (Schobert 2013).

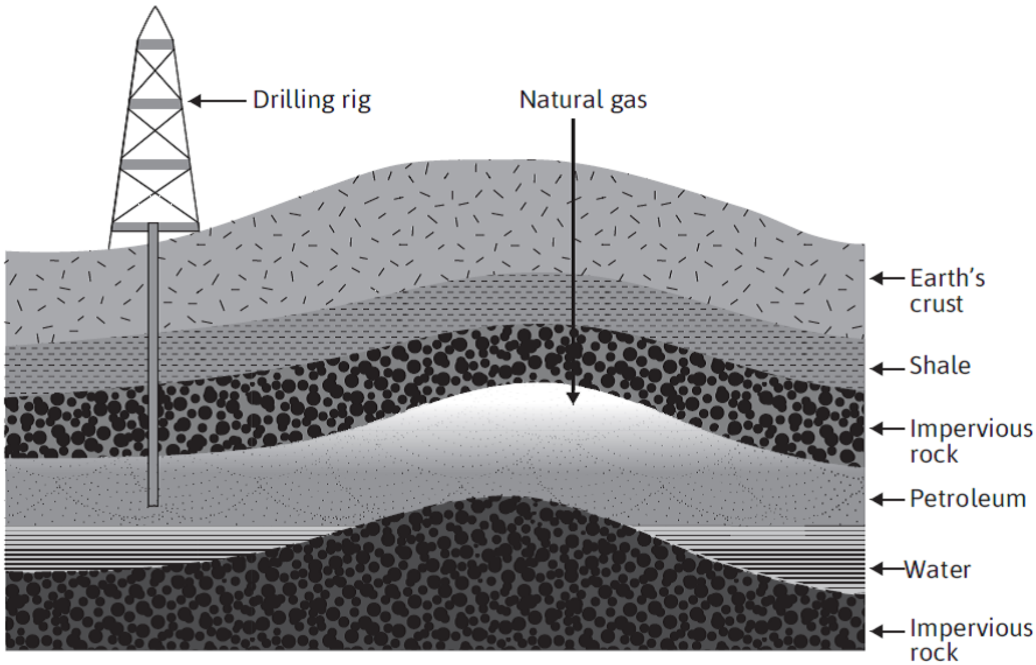


Figure 1.2: Petroleum and natural gas reservoir cross-sectional view (Terry et al. 2015)

1.3.3.1 Coal

Coal has more complex composition relative to petroleum and natural gas. As with petroleum, burning coal produces some ash coming from inorganic materials contained within it. The coal ash produced is far greater than petroleum ash, and makes up more than 25% of the coal weight. The complexity of coal compositions makes it difficult to categorize the various types of coals. However, there are some classifications for trade and research purposes. The classification for research purposes is determined by the amount of carbons, while in industry they are categorized by the amount of heat. In the US, the rank provided by American Society for Testing and Materials (known as ASTM) is often used, see Terry et al. (2015). Different kinds of coals are used in different applications. For instance, coking coal (metallurgical coal) is fed into a furnace with iron in order to generate and maintain heat for steel production. Also, *steam coal* is used to generate heat to rotate the turbine for electricity production (Terry et al. 2015).

1.3.3.2 Natural Gas

Natural gas is in the gas phase or dissolved in the petroleum reservoir. There are two types of natural gas:

1. Associated gas – is in contact with the petroleum. Associated gas can be classified into two categories: (a) gas dissolved in petroleum (dissolved gas), and (b) gas above the petroleum (gas-cap gas).

2. Non-associated gas – is not in contact with petroleum. This type of gas (counts for 60% of the world's natural gas) separates from the petroleum and migrates to a different location.

For further details please see Schobert (2013).

1.3.3.3 Petroleum

The root of the word *petroleum* goes back to the ancient Persian word *naphtha*, which means liquid coming out from the ground. The word was pronounced in other languages differently, e.g. Arabic: naft, Czech: nafta (Smil 2017b). Petroleum requires refinement before going to market, thus it is also called crude oil. The elemental compositions of petroleum are: carbon (82-87%), hydrogen (11-15%), sulfur, oxygen, and nitrogen. Depending upon the reservoir, the proportion of the last three substances varies.

Petroleum is shipped to a refinery to be separated into different fractions to enhance the quality. The main products of a refinery are consumed by transportation vehicles. A portion of refined products is sent to the polymer and chemical industry. In each refinery, different operations make commercial products, but the objective is not to separate all existing petroleum compounds. The desalting and distillation are the main operations often carried out in a refinery.

The distillation products need to pass through further stages to be transformed into commercial products. For instance, gasoline requires more hydrogen in order to improve combustion, so hydrogenates are added. For more detailed technical explanations on the refinery processes and products refer to (Meyers and Meyers 2004; Leprince 2001; Nelson 1958; Gary et al. 2007). In general the main products of the distillations are as follows:

1. Gasoline – produced from overhead steam in the distillation tower. Gasoline is currently the most important energy source in the world. In the US over 50% of the petroleum is converted to gasoline to meet consumer demand.

2. Naphtha – has two types: light naphtha with boiling points less than heavy naphtha. Naphtha is rarely employed as fuel directly, e.g. camping portable stove.

3. Kerosene – historically kerosene was used as lamp fuel before the advent of electricity. Currently, kerosene is further processed to produce jet fuels. Also, low quality kerosene (tractor vaporizing oil) is used in agriculture machinery.

4. Diesel fuel – initially derived from plants is known as biodiesel. In the 1890's Rudolf Diesel invented an engine, fueled by this. Currently many light and heavy vehicle engines are powered by diesel derived from petroleum, while ships use a heavier diesel.

5. Fuel oils (heating oils) – are used in domestic and industrial facilities for heating.

6. Lubricating oils (lube oils) – are usually produced by vacuum distillation, and used for reducing friction and heat between touching components, e.g., grease and asphalt. Refiners prefer to produce these oils due to their profitability.

7. Waxes – are in a solid form at ambient temperature. Initially they were produced for candle making, but currently are used in chemical, pharmaceutical, and cosmetic industries for producing skin moisturizers and softeners.

Figure 1.3 shows a schematic distillation tower and its products (Ashraf and Al Aftab 2012). As can be observed, gasoline (the main transportation fuel in the world) is produced from petroleum (U.S. Energy Information Administration 2015; Kessel 2000). Gasoline, the focus of this research, receives greater emphasis from this point onward. It is notable that there are many other processes which might take place in refineries, that are not aligned with the objective of this thesis, but interested readers may see Ashraf and Al Aftab (2012).

1.3.4 Bioethanol

According to the Renewable Fuel Standard 2 (RFS2), bioethanols (explained in Section 1.4.2) are categorized based upon their GHG emission reduction: 1^{st} generation (conventional bioethanol), 2^{nd} generation (cellulosic bioethanol), and 3^{rd} generation. Each generation is derived from a certain type of feedstock. For example, 1^{st} generation bioethanol is produced from corn and sugar cane, and the 2^{nd} generation is produced from corn stover. For the production process details see Brown and Brown (2013); Papari and Hawboldt (2018); Ringer et al. (2006); Mohan et al. (2006); Cottam and Bridgwater (1994); Krutof and Hawboldt (2018).

1.4 Environmental and Energy Security Policies

This section consists of two subsections. The first investigates international environmental agreements, while the second encompasses US environmental policies, as the US is the world's largest oil producer and consumer.

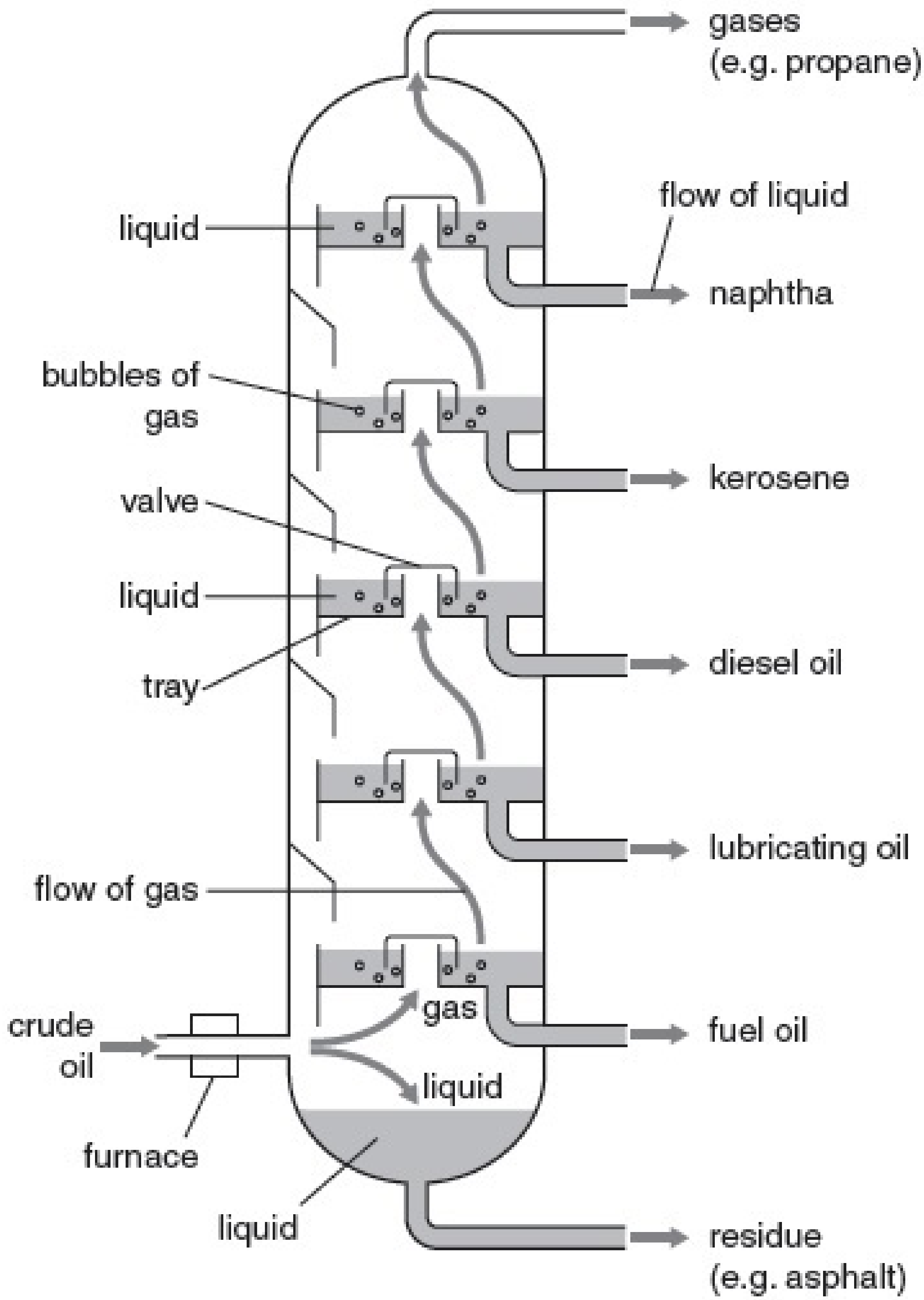


Figure 1.3: Distillation tower and its products (Ashraf and Al Aftab 2012)

1.4.1 International Environmental Agreements

F. S. Rowland and M. Molina, two chemists at the University of California, Irvine, started researching the effects of Chlorofluorocarbons (CFCs) on the atmosphere. Their findings showed that CFCs break down ozone (O_3), creating a hole in the ozone layer, resulting in harm to human health and the environment (Rowland 1996; 1989). Research in this direction led to the Vienna Convention for the Protection of the Ozone Layer, in 1985. This agreement, which was signed by 197 states (all United Nations (UN) members and some other parties), gave a framework for the reduction in production of CFCs (Albrecht 2014). This was the foundation of the Montreal Protocol on Substances that Deplete the Ozone Layer, signed in 1987, for details see Parmann et al. (2013); Velders et al. (2007); Protocol (1987).

In 1990, during the 45^{th} general assembly of the United Nations (UN), the United Nations Environment Programme and World Meteorological Organization (WMO) supported the formation of the Intergovernmental Negotiating Committee (INC) to establish the Framework Convention on Climate Change (FCCC). INC prepared the FCCC in its 5^{th} meeting held in May 1992. This was open for signatures at the Earth Summit, which is also known by two other names: the United Nations Conference on Environment and Development, and the Rio de Janeiro Earth Summit, held in Brazil during June 1992, for further information refer to Agrawala (1998); Bodansky (1993); Gupta (2010).

In the 2011 UN Climate Change Conference (UNCCC), all parties realized that their efforts to reduce GHG had been inadequate. Therefore, at the 2015 UNCCC, the parties ratified the Paris Agreement, which targeted limiting the increase of temperature to less than 1.5 – 2 degrees Celsius. This will come into force in 2020. Based upon this, each party must prepare their plan for GHG mitigation and report the progress in Conference of Parties (Rogelj et al. 2016; Hulme 2016).

There are some other international treaties, e.g. the Bali Action Plan, the Copenhagen Accord, the Cancún agreements, the Durban Platform for Enhanced Action, and the Nationally Determined Contributions, each agreed upon in 2007, 2009, 2010, 2012, and 2013 respectively Christoff (2008), Ramanathan and Xu (2010), Den Elzen et al. (2012), Rajamani (2012), and Richards et al. (2016).

1.4.2 US Environmental and Energy Security Policies

The US has been the world's biggest petroleum producer and consumer. Gasoline makes up more than 60% of transportation fuel in the US (U.S. Energy Information Administration 2018a). To control the consumption of gasoline due to earlier mentioned disadvantages, bioethanol produced from locally available biological materials was introduced as an alternative fuel. Currently, bioethanol (E100 i.e. 100% bioethanol) is used for vehicle transportation fuel in Brazil and as a gasoline additive (E10, E15 and E85) in the US, Canada, and India. In the US, all gasoline vehicles can use E10 (10% blend of bioethanol with 90% gasoline), those of model 2001 or greater can use E15, and E85 can be used by flex-fuel vehicles (FFVs). Currently, the US automobile manufacturers sell flex-fuel vehicles at no extra cost (U.S. Energy Information Administration 2016).

Between 1970 and 1973, the Organization of Petroleum Exporting Countries (OPEC) doubled the price of oil. In 1973 Arab Oil Ministers sanctioned the US, creating an energy crisis in that country. This led American policymakers to view agricultural products as a renewable source of fuel, more precisely bioethanol production. The initial main law, the National Energy Act of 1978, was ratified. This Act includes the Energy Tax Act (ETA), which aimed to lead the energy market towards renewable energies by providing tax incentives in order to become less dependent upon oil and gas. According to the ETA, gasoline blended with at least 10% volumic bioethanol would be exempted from a $0.4 per gallon motor fuel excise tax. In 1984, the Deficit Reduction Act increased the fuel excise tax exemption to $0.60 per gallon. In 1980, the Energy Security Act was implemented. According to this Act, the Secretaries of Energy and Agriculture were directed to prepare a plan for increasing the bioethanol production to at least 10% of gasoline demand annually. Also, it guaranteed loans to small bioethanol companies. In the 1980*s* and early 1990*s*, oil prices returned to normal value, increasing the competition between bioethanol and gasoline prices. Consequently, the government supported bioethanol production by the Deficit Reduction Act. However, in 1998, after over two decades of increasing the support for blending bioethanol with gasoline, the Transportation Equity Act reduced the tax credit to $0.53, $0.52, and $0.51 per gallon respectively starting in 2001, 2003, and 2005 (Duffield et al. 2008). This tax was extended by the 2004 American Job Creation Act (AJCA), which included energy concerns as having an impact on employment. This aimed to make the US "manufacturing, service, and high-technology businesses and workers more competitive and productive both at home and abroad" (Clausing 2004). The AJCA contains a section entitled "Tax Relief for Agriculture and Small Manufacturers", which has a subsection called "Volumetric Ethanol Excise Tax Credit", that extended the bioethanol tax credit of $0.51 per gallon to 2010 (Duffield et al. 2008). In 2009, the credit was reduced to $0.45 per gallon, which expired in 2011. To increase the market for local bioethanol, a $0.54 per gallon tariff for imported bioethanol was created (McPhail et al. 2011).

In 1988, the Alternative Motor Fuels Act was enforced. Accordingly, automobile manufacturers were motivated by a tax credit to produce vehicles consuming alternative fuels, i.e FFVs (Duffield et al. 2008). This Act might increase the demand for bioethanol; however, there might be more FFVs, but owners might still prefer to consume gasoline. Therefore, this Act may not have a direct impact upon SPSCs.

Researchers had determined that pollution was harmful for several reasons, as evidenced by a negative impact on citizen health, agriculture products, livestock, and property. Therefore, in 1955, the first US environmental law, the Air Pollution Control Act was ratified. This Act did not create any commitments for polluters to reduce emissions, but opened a path for more research into pollution control. The Act, which was of a five year duration, assigned a budget of $\$5 \cdot 10^6$ for the research (Schnelle Jr et al. 2015).

Later, efforts towards creating commitments for polluters emerged. The first action in this direction occurred when Congress passed the Clean Air Act of 1963. In this Act emission standards were set for stationary sources of emission, e.g. power plants and steel mills. However, it did not take into account the main source of pollution, i.e. automobile emissions. There were several amendments to this Act, in the years 1965, 1966, 1967, and 1969 that invoked deadlines for compliance to reduce emissions from automobiles.

Beginning with the first US environmental law, the government recognized that in order to increase efficiency in controlling air pollution it needed to customize pollution controls based upon the needs of each state. Therefore, the Air Quality Act of 1967 focused more on research and development of air pollution controls, by allocating budgets to individual states and communities. It also provided financial aid to states to design their own plans for inspection of vehicle GHG emissions. Some other issues included under this Act were the formation of an advisory board to help the Department of Health, Education, and Welfare to manage the emissions, and the registration of fuel additives that enhance the fuel quality (Middleton 1968).

Unfortunately, not a single state came up with a complete program for air pollution control, the desired aim of the Air Quality Act of 1967. Therefore, the US government sought to implement more serious action in this regard. Hence, a few months after the first Earth Day was celebrated in 1970, to enhance public consciousness about environmental problems, Congress passed a strict environmental law known as the Clean Air Act of 1970 (Rogers 1990). According to this Act, federal and state governments were authorized to prepare programs for both stationary and mobile sources of the emissions. The former was mainly regulated through the programs created by following: the National Ambient Air Quality Standards (NAAQS), the State Implementation Plans (SIPs), the New Source Performance Standards (NSPS), and the National Emission Standards for Hazardous Air Pollutants (NESHAPs). The Act also brought into existence the Environmental Protection Agency (EPA) with the responsibility for environmental legislation (Ross et al. 2012).

After experiencing the positive impact of the Clean Air Act of 1970 towards controlling emissions, the US government sought to improve it with two amendments: the Clean Air Act Amendment (CAAA) of 1977 and the CAAA of 1990 (U.S. Environmental Protection Agency 2017a). Resulting from this, two programs were established: the Reformulated Gasoline (RFG) and the Oxygenated Fuels. This mandated the selling of fuels with 2% oxygen, making bioethanol a perfect match for blending with gasoline. However, the petroleum industry began using Methyl Tertiary Butyl Ether (MTBE), also a petroleum based product. The Energy Policy Act of 1992, through its fuel excise tax exemption, enabled bioethanol to compete with MTBE. The tax credit drastically helped bioethanol production to reach almost $1.5 \cdot 10^9$ gallons annually in 1999 (Caldwell 2007) (MTBE was banned in California in 1999 as it was discovered that it is a ground and surface water contaminant, leaving bioethanol as the only source of gasoline oxygenate. Gradually other States followed the same practice). The Corn Belt states: Indiana, Illinois, Iowa, Missouri, eastern Nebraska and Kansas, gave maximum attention to bioethanol (derived from corn) production, since they harvested huge amounts of corn annually. Employment created by new bio-refineries and corn businesses enhanced these regions economically and socially (Duffield et al. 2008).

The 1998 Transportation Equity Act reduced the tax credit for blending bioethanol with gasoline for the 21^{st} century. Early in the present century, the global oil market experienced another shock, as world energy consumption increased and accelerated the price of oil past $30 per barrel. In 2001 in the US, this imbalance between supply and demand showed its destructive impact through increased cost to families, blackouts and brownouts, and the layoff of some employees. In response to the global energy shortage and following the emphasis that the president placed on domestic energy production and environmental conservation, two decisions were needed, to find an instant remedy for the shortage, and find a long term plan. Therefore, in 2000, the US Department of Agriculture introduced the Commodity Credit Corporation (CCC) Bioenergy Program. Under the CCC, bio-refineries were categorized into two classes: small bio-refineries having less than $65 \cdot 10^6$ gallons, and larger bio-refineries producing beyond that volume. The government reimbursed the cost of one unit of feedstock for each 2.5 units used in small bio-refineries, while, the big bio-refineries received the cost of one unit of feedstock for each 3.5 units used. Extra annual production of bio-refineries as compared to the former fiscal year was eligible for this incentive. This cost the government 40.7, 78.7, 150, 150, and 43.7 million dollars for each year 2001-2005 respectively (Shapouri and Gallagher 2005). For the long term plan, President George W. Bush's National Energy Policy Development Group developed a proposal entitled "Reliable, Affordable, and Environmentally Sound Energy for America's Future" (U.S. National Energy Policy Development Group 2001). To the best of our knowledge, this is the first US legal document that clearly shows the government is creating and leading the sustainable energy supply chain through legislation that has an impact, environmentally, economically and socially. Based on this proposal, several pieces of legislation were ratified, as discussed below.

The Farm Security and Rural Investment Act (the 2002 Farm Bill) was enacted in 2002. Subtitle IX within the Farm Bill entitled "Energy" supported development of bio-refineries and bio-products through new grants and programs. It also assisted qualified farmers to develop their own bio-refineries (U.S. Congress 2002). This Act encompasses long term plans for increasing the capacity of bioethanol production.

In 2005, the Energy Policy Act passed by the US congress resulted in Renewable Fuels

Standard (RFS), which mandated renewable fuel consumption, thus guaranteeing a market for bioethanol and a change in the SC. Title XV, bioethanol and motor fuels, elaborated on this issue and defined the term "renewable fuel" as, a motor vehicle fuel which is

- produced from grain, starch, oil-seeds, vegetable, animal, or fish materials including fats, greases, and oils, sugarcane, sugar beets, sugar components, tobacco, potatoes, or other biomass;
- natural gas produced from a biogas source, including a landfill, sewage waste treatment plant, feedlot, or other place where decaying organic material is found;
- derived from any lignocellulosic or hemicellulosic matter that is available on a renewable or recurring basis, including–(i) dedicated energy crops and trees; (ii) wood and wood residues; (iii) plants; (iv) grasses; (v) agricultural residues; (vi) fibers; (vii) animal wastes and other waste materials; and (viii) municipal solid waste, which is called cellulosic biomass ethanol;
- biodiesel (Public Law 2005).

After one year enactment of the law, the administrator had to ensure that mandated renewable fuel was blended with gasoline available in the US market. To do this, administrators were authorized to issue or revise the regulations to include the compliance provisions for obligated parties (i.e. refineries and importers of gasoline), and determined the applicable percentage of renewable fuel that had to be blended.

As of 2013 and later the applicable volume has been calculated according to the following formula:

$$\text{Estimated gasoline consumption for the coming year} \cdot \left(\frac{7.5 \cdot 10^9}{\text{gasoline sold in the market in 2012}}\right)$$

However, before mandating anything for 2013 and later, the impact of legislation on the environment, energy independency, and society (e.g. job creation) must be evaluated.

All refineries (with production capacity above 75000 barrels per day) and importers of gasoline, are mandated to use enough renewable fuel to generate credits, to meet the government created mandate. Each gallon of cellulosic bioethanol has 2.5 credits, while other renewable fuels receive one credit per gallon. Credit generated by blending renewable fuel into gasoline is valid for one year. The credit can be transferred from the person who generated it, to other persons, for the purpose of compliance with the renewable fuel mandate. Obligated parties are permitted to carry the deficit from one year to the next, if they cannot meet the obligation through generating enough credits or by purchasing them. “The Administrator, in consultation with the Secretary of Agriculture and the Secretary of Energy, may waive the renewable fuel requirements” (Public Law 2005).

According to the 2005 Energy Policy Act, about 6 months after implementation of RFS, the Secretary of Energy had to conduct research on three significant issues of the newly mandated supply chain:

1. Supplies and prices of renewable fuels;
2. Blendstock supplies;
3. Renewable fuels supply and distribution system capabilities.

This study would be helpful in the waiving of renewable fuel mandates. To our knowledge, the 2005 Energy Policy Act is the first legislation that directly aimed to create a market for bioethanol. This converts the Conventional Petroleum Supply Chain to a Sustainable Petroleum Supply Chain.

Furthermore, the 2005 Energy Policy Act includes a provision called the “Cellulosic Biomass Loan Guarantee Program”. According to this, the secretary must set up a program to provide financial support in terms of loans to businesses interested in establishing facilities for the processing and conversion of cellulosic biomass.

Experiencing the positive influence of the 2005 Energy Policy Act, the government decided to extend the Act further while increasing the mandated volume amount in order to create

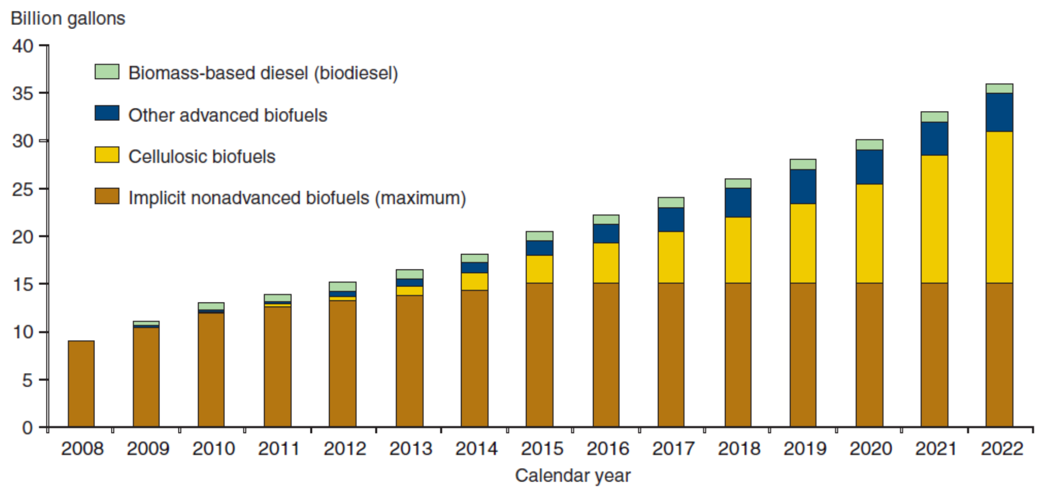


Figure 1.4: Renewable Fuel Standard (RFS2) mandate by different types, 2008-2022 (U.S. Congress 2007)

a secure bioethanol market for longer investment, and become more independent from oil. Therefore, in 2007, the Energy Independency and Security Act was passed by Senate and House of Representatives. This aimed to

> move the United States toward greater energy independence and security, to increase the production of clean renewable fuels, to protect consumers, to increase the efficiency of products, buildings, and vehicles, to promote research on and deploy greenhouse gas capture and storage options, and to improve the energy performance of the Federal Government, and for other purposes (U.S. Congress 2007).

This act categorizes biofuels based on their life-cycle greenhouse gas emissions reduction, see Figure 1.4.

The greenhouse gases are "defined carbon dioxide, hydrofluorocarbons, methane, nitrous oxide, perfluorocarbons, sulfur hexafluoride". Similarly, the definition for life-cycle greenhouse gas emissions is

> the aggregate quantity of greenhouse gas emissions (including direct emissions and significant indirect emissions such as significant emissions from land

use changes), as determined by the Administrator, related to the full fuel lifecycle, including all stages of fuel and feedstock production and distribution, from feedstock generation or extraction through the distribution and delivery and use of the finished fuel to the ultimate consumer, where the mass values for all greenhouse gases are adjusted to account for their relative global warming potential (U.S. Congress 2007).

The 2007 Energy Independency and Security Act defines renewable fuel, as "fuel that is produced from renewable biomass and that is used to replace or reduce the quantity of fossil fuel present in a transportation fuel" (U.S. Congress 2007). According to the Act, bioethanol can be produced from different types of feedstock such as corn and sugar (called 1^{st} generation or conventional biofuel) with 20% GHG emission reduction; corn stover and straw (called 2^{nd} generation or cellulosic) with 60% GHG emission reduction; and algae (called 3^{rd} generation) with 50% GHG emission reduction (Baeyens et al. 2015). Based on the nested structure of RFS2, the fuels having higher emission reductions can be used to meet the mandate for other categories (U.S. Environmental Protection Agency 2017c). Biofuel production from the 1^{st} generation feedstock is limited in order to maintain food security (Sharma et al. 2013). Furthermore, the 3^{rd} generation is still under investigation and not yet commercialized (Baeyens et al. 2015). The 2^{nd} generation has received considerable attention from different entities like governments and investors (Gupta and Verma 2015). The renewable fuel volume (in billions of gallons) for 2006 - 2022, is shown in Table 1.2 (U.S. Congress 2007).

2006	2007	2008	2009	2010	2011	2012	2013	2014
4	4.7	9	11.1	12.95	13.95	15.2	16.55	18.15
2015	2016	2017	2018	2019	2020	2021	2022	
20.5	22.25	24	26	28	30	33	36	

Table 1.2: Applicable renewable fuel volume (in billions of gallons) for 2006 - 2022 (U.S. Congress 2007)

Similarly, for the cellulosic biofuels and third generation biofuel, the standards are illustrated in Table 1.3 and Table 1.4 respectively.

2010	2011	2012	2013	2014	2015	2016
0.1	0.25	0.5	1	1.75	3	4.25
2017	2018	2019	2020	2021	2022	
5.5	7	8.5	10.5	13.5	16	

Table 1.3: Applicable cellulosic biofuels volume (in billions of gallons) for 2010 - 2022 (U.S. Congress 2007)

2009	2010	2011	2012	2013	2014	2015
0.6	0.95	1.35	2	2.75	3.75	5.5
2016	2017	2018	2019	2020	2021	2022
7.25	9	11	13	15	18	21

Table 1.4: Applicable third generation biofuel volume (in billions of gallons) for 2009 - 2022 (U.S. Congress 2007)

For the years after 2020, the applicable volume must be determined after analyzing (U.S. Congress 2007):

1. the impact of the production and use of renewable fuels on the environment, including on air quality, climate change, conversion of wetlands, ecosystems, wildlife habitat, water quality, and water supply;

2. the impact of renewable fuels on the energy security of the United States;

3. the expected annual rate of future commercial production of renewable fuels, including advanced biofuels in each category (cellulosic biofuel and biomass-based diesel);

4. the impact of renewable fuels on the infrastructure of the United States, including deliverability of materials, goods, and products other than renewable fuel, and the sufficiency of infrastructure to deliver and use renewable fuel;

5. the impact of the use of renewable fuels on the cost to consumers of transportation fuel and on the cost to transport goods;

6. the impact of the use of renewable fuels on other factors, including job creation, the price and supply of agricultural commodities, rural economic development, and food prices.

The 2007 Energy Independency and Security Act, known as RFS2, which is an extension to the 2005 Energy Policy Act, categorized bioethanols based on their life-cycle GHG emission reduction. It also considered giving equal credit for different categories, e.g., one gallon of cellulosic bioethanol has the same credit as one gallon of first generation bioethanol. RFS2 requires that US fuel producers, gasoline refiners and gasoline importers into the US (called obligated parties), blend at least a minimum amount of renewable fuels (called by two names: Renewable Volume Obligations (RVOs) or Mandate) with their production annually. The RVOs are met by having enough Renewable Identification Numbers (RINs), which were created by the United States Environmental Protection Agency (EPA). A RIN is a serial number allocated to a batch of biofuel by registered US biofuel producers located in the US and/or registered biofuel importers into the US, in order to track production, trade and consumption of biofuels. A RIN moves with the batch of biofuel when the biofuel is traded and are separated when the biofuel is used, such as when bioethanol is blended with gasoline. If the separated RINs are used for compliance with RVOs by the party separating them, then RINs are considered retired. However, the separated RINs can be sold to other obligated parties. An example of the RIN life-cycle is illustrated in Figure 1.5 (U.S. Environmental Protection Agency 2007).

For instance, a refinery produces $5 \cdot 10^9$ gallons of gasoline in a year, for which the cellulosic mandate is 2%, the refinery should blend $5 \cdot 10^9 \cdot (0.02) = 10^8$ gallons of cellulosic bioethanol with its gasoline. This helps the refinery to have enough RINs for compliance with RFS2. Otherwise, it would need to buy the separated RINs.

The guaranteed bioethanol market created by the Renewable Fuel Standards (RFS1 and

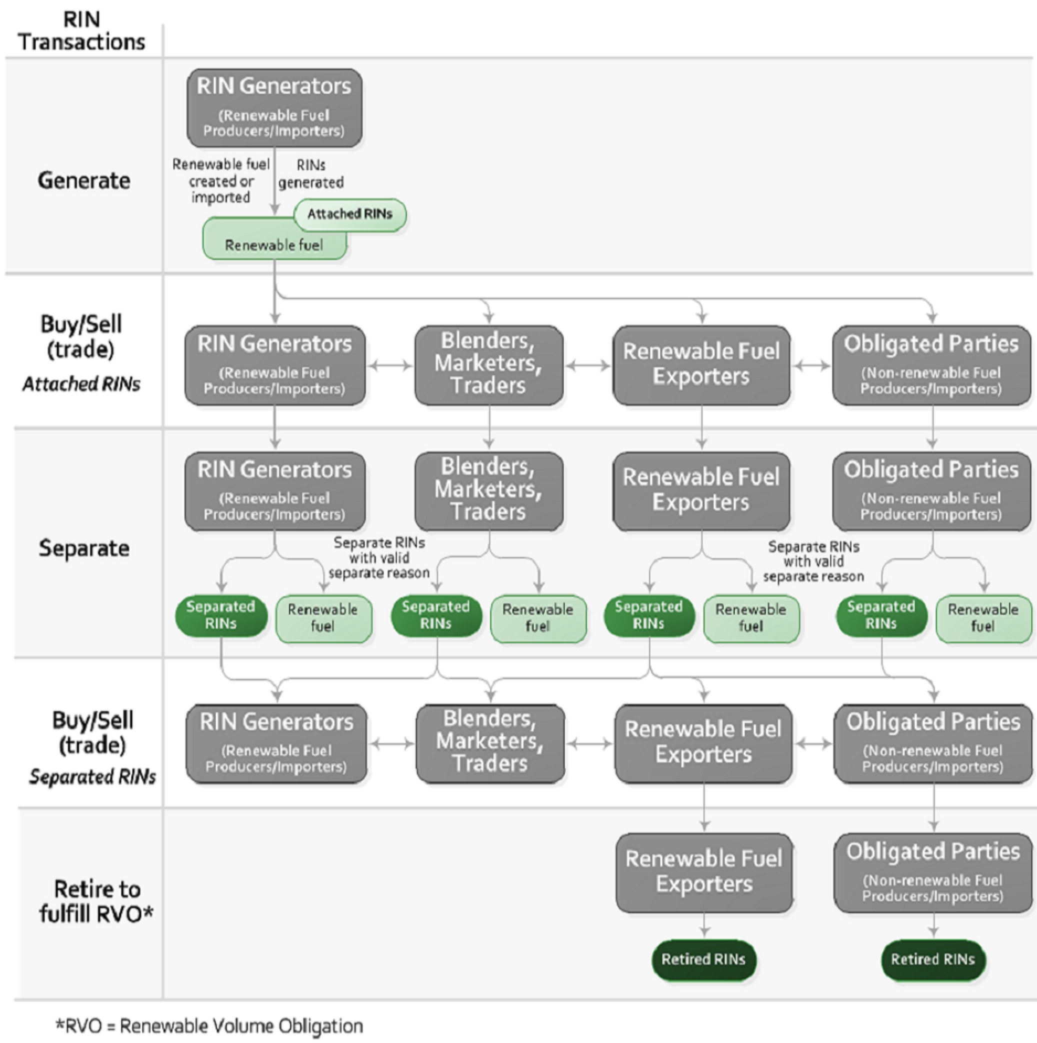


Figure 1.5: Renewable Identification Number's life-cycle (U.S. Environmental Protection Agency 2007)

RFS2) attracted businesses to invest in bio-refineries establishment for the production of different generation bioethanol. To enhance profit, more efficient Bioethanol Supply Chains (BSCs) were created. For instance, bio-refineries with advanced technologies capture a greater market share. The BSCs and the Conventional Petroleum Supply Chains were merged to create the Sustainable Petroleum Supply Chains (SPSCs) to meet the required RINs. In some cases, refineries and bio-refineries were blending more bioethanol to increase profits. In 2009, the Growth Energy company on behalf of 52 other companies, applied to the EPA for a waiver on the Clean Air Act (CAA), which was limiting the amount of bioethanol blended with gasoline. In 2010, EPA accepted the application for blending up to 15% bioethanol with gasoline (E15) for passenger and light vehicles of model year 2007 and later. In 2011, it was extended for the vehicles of model year 2001 and later. This partial wavier helped towards meeting RFS2.

According to CAA, all gasoline engine vehicles are permitted to use up to 10% bioethanol blended with gasoline (E10); however, Flex-Fuel Vehicles (FFVs) are allowed to use up to an 85% blend. The maximum amount of bioethanol (10%) which can be blended with each gallon of gasoline to be used in all gasoline engine vehicles is called Blend Wall (BW). Yacobucci (2010) provides further details on the BW.

1.5 Literature Review and Gaps

1.5.1 Supply Chains

A Supply Chain (SC) is defined as,

> "an integrated network of raw materials, the transformation of these materials into intermediate and finished products, and distribution of the finished products to the final customers" (Goetschalckx 2011).

Supply Chain Management (SCM) is management of a complex and dynamic supply network of integrated companies or organizations which are involved in satisfying the final customers' demand (Shapiro 2004). According to Beamon and Chen (2001), all SC structures fall in four categories:

1. Convergent – Each partner (supplier, facility, distributor, etc.) in this kind of SC has at most one successor, but may have a different number of predecessors. Due to its application, often in assembly-type structures, it is sometimes referred to as an assembly structure. Shipbuilding, and building construction are examples of this structure.

2. Divergent – Each partner has at most one predecessor in this kind of SC, but may have any number of successors. The tree look of this SC has resulted in it also being called arborescent. This is opposite to the assembly (convergent) structure. Fishing and mineral industries have divergent structure.

3. Conjoined – Merging convergent and divergent structures sequentially forms this SC. Online retailers, for example, have this type of structure.

4. General – Any structure which does not fall in any of the three categories above, is called general or network structure. For example, car manufacturing companies receive their components from different suppliers, and after assembly their products are shipped to different distributors.

To have a deeper knowledge regarding the structures, please see Table 1.5.

Following on this line, later Huang et al. (2003) extend the classification and categorize SCs into five classes: dyadic, serial, divergent, convergent, and network. There are only two new terms; *dyadic*, indicating that only two partners exist in the SC (i.e. supplier and

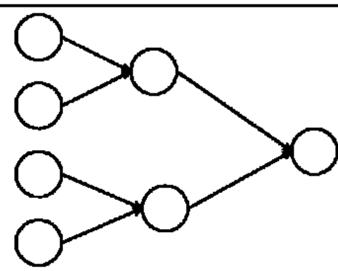
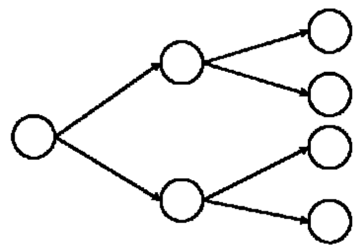
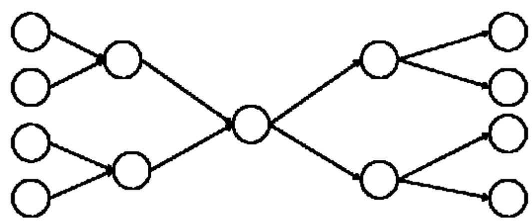
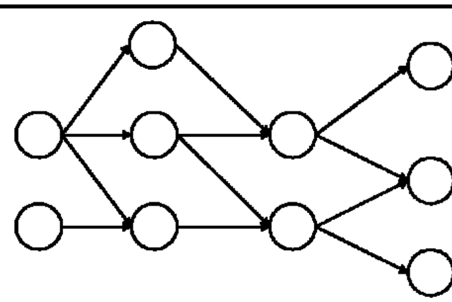
Classification type	Example
Convergent (assembly)	
Divergent (arborescent)	
Conjoined	
General (network)	

Table 1.5: Supply Chain structure classifications (Beamon and Chen 2001)

manufacturer), while *serial* refers to several joint dyadic SCs. Mula et al. (2010) argue that most supply chain studies have focused on dyadic and serial structures, although the real-life SCs are often network structures, involving a great deal of computational complexity. On this line, this thesis contributes by developing a real-life network structure SPSC, and proposing an approach to overcome the complexity.

The significance of SCs and their competitiveness in the existing complicated and dynamic market is well recognized. Thus, to manage an SC well and stay in the market, prudent decisions are of importance. Each SC categorizes its decisions based on their frequency and time horizon in the following classes (Sahebi and Nickel 2014):

1. Strategic or design decisions – These sorts of decisions are often made for matters spanning a long duration, and costly to alter; for instance, locations and the capacity of the facilities fall within this category. Therefore, the SC managers aim to make robust decisions, accounting for uncertain factors, e.g., market price fluctuation.

2. Planning or tactical decisions – They are often made for matters that have a life-cycle from a quarter to a year. With strategic decisions in place, planning decisions should be made. For example, companies need to decide which facility is supplied by which supplier(s) and which market zone is supplied by which facilities.

3. Operational decisions – These decisions are made for daily or weekly issues, following on strategic and tactical decisions. In other words, the goal is to respond to the incoming customers in the most efficient manner. A deadline for meeting orders, and scheduling production are examples of these decisions.

Researchers and practitioners believe integrating these three decision levels promotes SCs success. However, it is usual for strategic and tactical decisions to be integrated, considering the resources required and the efficiency obtained (Chopra and Meindl 2001; Huang

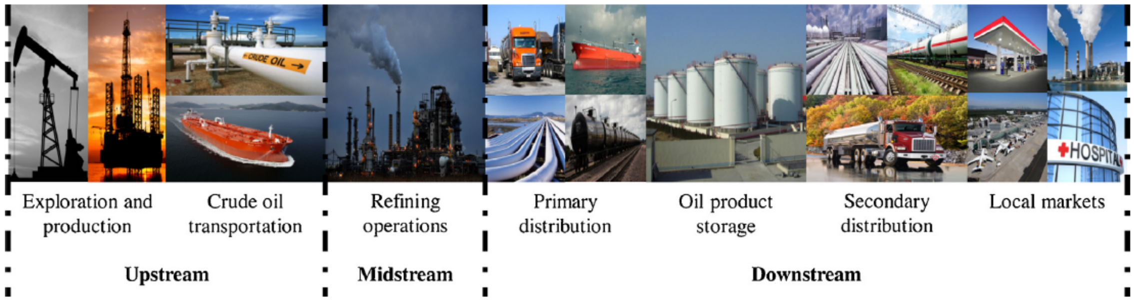


Figure 1.6: CPSC different streams (Lima et al. 2016)

et al. 2003). Therefore, we also integrate strategic and tactical decisions in the SPSCs in this thesis.

1.5.1.1 Conventional Petroleum Supply Chains (CPSCs)

The price of petroleum, also referred to as oil, is the most important price in the world, and is a great proxy for world economic activity. Thus, a perfect management of its supply chain, from well-to-wheels, is also very vital for the world. The Conventional Petroleum Supply Chains (CPSCs), or Conventional Crude Oil Supply Chains (CCOSCs), are often categorized into three segments: upstream, midstream, and downstream, see Figure 1.6. The upstream segment refers to anything from exploration to refineries. The midstream segment addresses transformation and production of oil products. In the downstream segment the finished products are stored and distributed to customers (Sahebi and Nickel 2014).
Like any other SC, the decisions within CPSCs are very important in its success. Sahebi et al. (2014b) categorizes decision levels in CPSCs as follows:

1. Strategic decisions (design of the SC), having the time span of 5 - 20 years;
2. Planning decisions, lasting for the period of 0.5 - 2 years;
3. Operational decisions, dealing with weekly (or daily) activities;

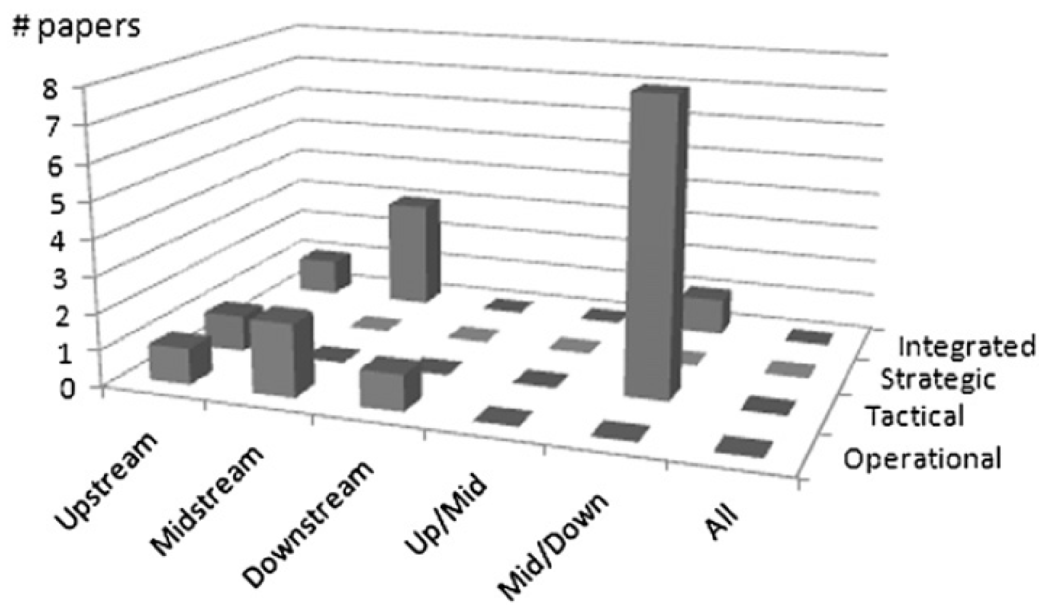


Figure 1.7: Classification of papers related to CPSC (An et al. 2011)

This shows strategic and tactical decisions in the CPSCs are very significant. Additionally, their integration results in 5 - 10% in costs (Goetschalckx et al. 2002). However, An et al. (2011) reviews studies devoted to different decision levels in CPSCs and presents the result in a three dimensional graph, see Figure 1.7. Their research indicates, studies have very rarely integrated different decision levels and streams. Therefore, we address this gap in this thesis, given our focus is on downstream of the CPSC, where it merges with Bioethanol Supply Chain to become sustainable.

There are further research opportunities in CPSCs, which can be found in the most recent literature reviews by Sahebi et al. (2014b) and Lima et al. (2016). Sahebi et al. (2014b) reviews mathematical programming models of CPSCs, including strategic and tactical decisions, and provide the following research gaps, for example:

- Studying real life CPSCs;
- Creating efficient algorithms for solving the large scale real case problems of CPSCs;

- Integrating the strategic and tactical decisions;
- Optimizing Sustainable Petroleum Supply Chains (SPSCs).

On the other hand, Lima et al. (2016) focus on reviewing papers related to downstream of CPSCs. The authors offer the following directions for further research:

- Formulating bi-objective models to capture social and economic aspects;
- Integrating different decision levels and streams;
- Configuring SPSCs;
- Considering new incentives for integrating Bioethanol Supply Chains and CPSCs;

All these gaps are addressed in this thesis.

1.5.1.2 Bioethanol Supply Chains (BSCs)

Biomass Supply Chain is defined as "the integrated management of bioenergy production from harvesting biomaterials to energy conversion facilities" (Mafakheri and Nasiri 2014). Biofuel Supply Chain encompasses other entities like blending facilities, gas stations, and demand; this includes different sources of uncertainty such as the supply side, demand side and government side (Sharma et al. 2013; Adams et al. 2011).

The 1^{st} and 2^{nd} generation bioethanol, which are derived from biomass, are different types of biofuels. Therefore, we define a Bioethanol Supply Chain (BSC) as an integrated chain proceeding from harvesting biomass and ending with the vehicles for which it is produced. Similar to CPSCs, activities in BSCs are classified in three following categories:

1. Upstream, including biomass harvesting, collecting, and transportation to bio-refineries;
2. Midstream, comprising of bio-refineries only;

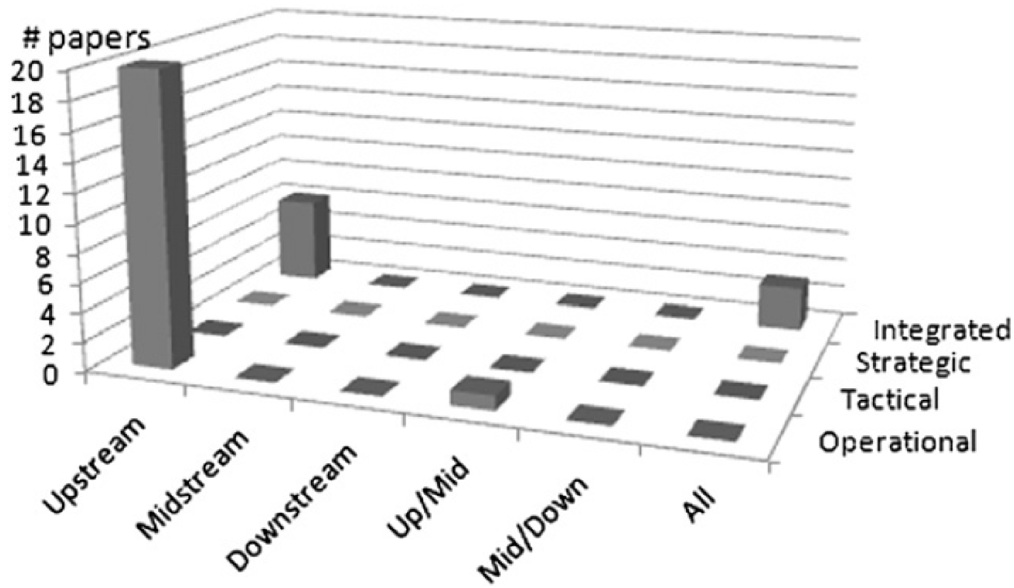


Figure 1.8: Classification of papers related to BSC (An et al. 2011)

3. Downstream, referring to transportation of bioethanol to blending sites for blending, storage, and final distribution.

The most recent reviews related to BSCs by An et al. (2011); Sharma et al. (2013); Mafakheri and Nasiri (2014); Ghaderi et al. (2016), offering insights on new avenues for further research. The review paper An et al. (2011) concludes few studies are carried out on the integration of decision levels and streams, see Figure 1.8.

Sharma et al. (2013) have a very comprehensive review, identifying several research gaps, some of which are as follows:

- Considering domestic energy legislation in the models;
- Developing efficient algorithms to solve large scale problems in BSCs;
- Developing stochastic models to handle uncertainty involved in different stages of BSCs, e.g. biomass supply due to weather, and governmental policies;

- Including different generations bioethanol;
- Configuring real life large scale SCs;
- Incorporating existing facilities into the models;

Later on, Mafakheri and Nasiri (2014) argue that governments should develop different policies to support BSCs. Furthermore, their review illustrates there is little research on social, economic, and environmental aspects of the BSCs. Thus, there exists a need for research to determine the impacts of supporting policies on BSCs.

Finally, Ghaderi et al. (2016), with their optimization focus and analysis review, provide the following research direction for further studies:

- The type of biomass available depends upon the country, not just an area's climate and geography. Thus conducting a case study in different regions may provide new insights;
- Bioethanol production is influenced by countries' political issues, therefore, it is significant to incorporate them in BSC models;
- Multi-objective models are needed to measure different perspectives of BSCs;
- Solution methodologies which can help researchers to reduce time complexity of large scale real world problems, and arrive at exact solutions, would be the most attractive research direction.

All the research gaps corresponding to BSCs mentioned in this section are addressed in this thesis.

1.5.1.3 Sustainable Petroleum Supply Chains (SPSCs)

Sustainability is often defined as using available resources in a way that may also be utilized by future generations. Initially, sustainability initiatives were directed towards environmental issues. Gradually economic and social aspects were included. A sustainable business can be defined as "the creation of resilient organizations through integrated economic, social and environmental systems" (Ahi and Searcy 2013). This means the organization is able to respond to difficulties more easily.

The concept of sustainability has been used in SCs, using two terms, Green Supply Chain Management (GSCM) and Sustainable Supply Chain Management (SSCM) (Ashby et al. 2012). Ahi and Searcy (2013) completed an interesting review on these two terms. They concluded that environmental issues play the key role in GSCM; when social and economic aspects are added as the main key factors, it is called SSCM.

As explained in Section 1.4.2, in the US, different environmental energy independency policies, e.g., RFS2 and Tax Credits, have joined BSCs with CPSCs, in order to enhance environmental and energy security issues corresponding to gasoline, the most consumed fuel in the US. Additionally, these policies create new business opportunities and jobs, particularly in rural areas. Therefore, given the definition of sustainability, the new SC, which is formed by merging BSCs and CPSCs in the downstream, is called SPSCs.

Only Andersen et al. (2013); Kazemzadeh and Hu (2013; 2015) study the SPSCs. Andersen et al. (2013) study strategic and tactical decisions of an SPSC, which includes only 2^{nd} generation bioethanol. Their SC includes: harvesting sites, bio-refineries, petroleum refineries, distribution centers (where blending also occurs), and the demand zones where transportation fuel is sold. They propose both a mathematical programming model to investigate the regions of the US which require investment to implement SPSCs, as well as a detailed model to study distribution of fuel within a state. In order to accomplish this, they employ a bi-level decomposition algorithm to solve the model, however, it still took over 3 hours to reach an optimality gap of 1%. Their models focus on cost minimization, do not include both the policies, the backbone of the SPSC, and uncertainty which is present in the BSCs (Awudu and Zhang 2012; Meyer 2007; Yue et al. 2014), and do not consider bioethanol imports and exports. Kazemzadeh and Hu (2013) employ risk neutral and risk averse approaches in their two models, in which they incorporate RFS2 and TCL. Later, they extend their work in Kazemzadeh and Hu (2015) and conduct a study on the impact of US government policies on SPSCs (considered 2^{nd} generation bioethanol) by studying strategic and tactical decisions. The authors considered RFS2 and Tax Credit (more precisely, focused on pass-through, which is the amount of the credit passed through the SC). They develop a stochastic model with an expected profit maximization objective function, to capture the uncertainty in government policies, fuel market price, biomass supply, and transportation and operation costs; also, CVaR for annual expected profit maximization objective function. They do not consider import and export of bioethanol in their model. To find the impact of the policies on SPSCs, a computational experiment was run with a total of nine scenarios, three scenarios for each, RFS2, and Tax Credit. Their research again underlines the need for new algorithms that not only provide solutions for a large number of instances in reasonable time but also provide key insights into the policy through those solutions. This thesis aims to fill these gaps by including in the proposed models: 1^{st} and 2^{nd} generation bioethanol, uncertain factors, imported bioethanol from other states and abroad, exporting bioethanol and a broader range of policies. Furthermore, we propose an approach to solve the computational complexity issue and provide more insights.

It is notable that Tong et al. (2014; 2013); Najmi et al. (2016) have studied drop-in biofuel SCs, which meet the general definition of SSCM. The drop-in biofuel has the same chemical properties of gasoline, while it is derived from biomass. Thus, it might be sold on the market without being blended with gasoline. Currently, drop-in biofuel does not exist in the market, and is thus referred to as the energy of the future (U.S. Department of Energy 2013). Therefore, in this thesis we do not consider drop-in biofuels.

There appears to be no research to adequately study SPSCs created in response to government policies, although policies are the underlying reason for the creation of SPSC, and it was emphasized as a research gap in Sharma et al. (2013); Lima et al. (2016); Ghaderi et al. (2016). Additionally, Vimmerstedt et al. (2012) also clearly mentioned that US government policies are required for survival of SPSCs using system dynamics. Studying SPSCs evolved due to government policies is significant, as it helps the government to understand how their policies would align with their sustainability objectives (in other words, economic, social, and environmental aspects); also, it clarifies for businesses the manner in which to invest in order to have the most robust business against policy change, while making maximum expected profit.

One practical case which reveals the significance of studying the SPSCs, incorporating the policies in the model, is, bankruptcy of Philadelphia Energy Solutions (the largest U.S. East Coast oil refinery), in 2018. The bankruptcy resulted in loss of jobs, and calls for changing some policies (Renshaw 2018; Willette 2018). The company blamed the RFS2 for the bankruptcy, see DiNapoli and Renshaw (2018). Furthermore, recently, Coronavirus Disease (COVID-19) and the 2020 Saudi Arabia-Russia Oil Price War resulted in more bankruptcies, see the biggest oil producer in North Dakota's Bakken region, Whiting Petroleum Corp (Nair 2020), Diamondback Industries (Posgate 2020), and Unit Corp (Taylor 2020); the number of bankruptcies is forecast to be over 1,100 companies (Egan and CNN Business 2020). Similarly, this has led to the closure of more than 70 bio-refineries (Neeley 2020). For instance, see Element (The Andersons Inc. 2020) and One Earth Energy (Voegele 2020b). These bankruptcies also clarifies the significance of creating resilient SPSCs to withstand economic crises, by hedging them against financial risks. This thesis aims to address this issue too.

1.5.2 Risk Management

Risk and uncertainty are formally distinguished by Frank (1921). He believes the dynamic world creates new business opportunities for people to make profits, however, on the other hand this means that we do not have perfect knowledge of future outcomes. Thus, risk refers to situations that their outcomes are unknown, but their odds can be determined accurately. On the other hand, uncertainty refers to situations that there is inadequate information to set accurate odds initially.

A leading factor in decision making of investors for creating the SPSCs is their risk preference, which is their attitude towards risks. The creation of SPSC is a high risk business venture, resulting from the inherent degree of uncertainty (Behrenbruch et al. 1989; Committee on Energy and Natural Resources 2007). The sources of uncertainty are several factors, e.g., taxes and tariffs (Yanting and Liyun 2011). Therefore, risk management, defined as, "a scientific management method to identify, measure and analyze risk and on this basis to deal effectively with risk, to achieve maximum security at minimum cost", is of much importance, especially when risk surges during economic crises (Yanting and Liyun 2011). Different risk preferences are usually resulted from cognitive biases and external factors, although overall people are risk averse during crises (Wen et al. 2014). That being said, there is no risk averse model, including all the supporting government policies, for the SPSC management, although the SPSCs has faced several economic crises, for example, currently COVID-19 and the Saudi Arabia-Russia Oil Price War have created economic catastrophe. We fill this gap in this thesis.

Sawik et al. (2018) argues investors in supply chains follow one of the three following decision making policies at each stage: (1) risk neutral, which concentrates on an average performance of a supply chain, and for example, is based expected profit maximization objective function; (2) risk averse, focusing on the worse case performance of a supply chain, and for instance applies Conditional Value-at-Risk (CVaR) of expected profit objective function; and (3) Mean risk, which is a combination of the first two policies, a trade-off between expected profit and CVaR of expected profit maximization objective function. In this thesis we consider risk neutral and risk averse approaches, respectively for investment on the SPSCs during regular economic conditions and economic crises.

Conditional Value-at-Risk (CVaR) is a measure of risk often used by businesses which are involved in investment, since their aim is to have optimal decisions in risky business environment, e.g., during economic crises, (Rockafellar et al. 2000). CVaR has been applied in SPSCs, which have been evolved in response to the US government policies, see the research performed by Kazemzadeh and Hu (2015). Also, CVaR has been employed by Gebreslassie et al. (2012a) and Carneiro et al. (2010) for ESCs and CPSCs respectively, both components of SPSCs. Gebreslassie et al. (2012a) and Carneiro et al. (2010) utilize CVaR for minimization of the expected annual cost and maximization the net present value (NPV) objective functions respectively. All of these studies demonstrate that CVaR is a highly effective metric for financial risk management. Therefore, in this thesis we also consider CVaR for our maximization of annual expected profit objective function. For further information on CVaR, please see Rockafellar et al. (2000); Ogryczak and Ruszczynski (2002); Rockafellar and Uryasev (2002b).

1.6 Modeling and Solution Techniques

In this thesis we are studying SPSCs created in response to government policies. To create SPSCs, the policies encourage establishing bio-refineries in some locations to process the limited supply of feedstocks. The bioethanol produced in those bio-refineries may be exported or shipped out to blending sites which also need to be established in some locations for blending bioethanol with gasoline and for storage. Finally, the fuel (bioethanol-gasoline blend) is shipped out from blending sites to distribution centers to meet demand for fuel. From this perspective, our problem looks like Location-Allocation (LA) problems in OR. LA problems are defined as “mathematical programs that seek the least cost method for simultaneously locating a set of service facilities and satisfying the demands of a given set of customers” (Sherali and Adams 1984); as in this thesis bio-refineries and blending sites are sought to be located to meet the demand for the fuel. Additionally, since the SPSCs in our research problems include *different types of facilities (or partners)*, it requires solving a Multi-echelon LA problem (Cooper 1963; Wang and Lee 2015; Shankar et al. 2013). Mixed Integer Linear Programming (MILP) may be applied to solve LA problems, if the variables are discrete and deterministic (Dolgui et al. 2006; Brimberg and Hodgson 2011). However, our research problems are discrete probabilistic problems; in reality, bio-refineries and blending sites can be located in some limited numbers of locations, and there are many uncertain factors in the SPSCs, e.g., demand for fuel, and supply of feedstock. Therefore, we use the stochastic programming method. More precisely we apply two-stage stochastic programming, since we want to integrate strategic and tactical decisions due to its importance, see Section 1.5.1. Consequently, the problems at hand are two-stage stochastic multi-echelon location-allocation problems.

The LA problem, even deterministic and single-echelon, is NP-hard. Due to the computational complexity of the LA problem the instances with large numbers of potential locations cannot be solved to optimality in reasonable time by standard solvers like Gurobi. Moreover, though some customized algorithms like a branch and bound algorithm of Kuenne and Soland (1972) have been proposed in the literature, it remains to be seen whether they can even compete with off-the-shelf optimization solvers, e.g., Gurobi. Therefore, the optimal solutions for the instances with large numbers of potential locations are out of reach in practice, and thus various heuristics have been proposed in the literature (Murray and Church 1996; Bischoff and Dächert 2009). The computational complexity grows further if the uncertainty is introduced in LA problems which is the case for this thesis. For instance, Chen and Fan (2012) employ the Progressive Hedging (PH) algorithm for solving a stochastic programming model with 8 scenarios, but they only reach a solution within 0.131% from the optimum after 2 hours, though without proving that the solution is optimal. Clearly showing that the solution found may be relatively close to the optimum (more precisely to either a lower or an upper bound obtained by relaxations) in reasonable time does not mean that the optimum itself can also be found in reasonable time since the proof of optimality is typically much more time consuming due to the problem NP-hardness. The computational complexity poses a formidable barrier in studying the SPSCs created due to government polices, based on optimization, since the analysis requires a large number of instances to be solved to optimality. This thesis proposes an approach, referred to as Lean Model (LM) (or its extension called Extended Lean Model (ELM)) to overcome this barrier, which fills a research gap on which a huge emphasis had been given in several recent review papers, see Sections 1.5.1.1 and 1.5.1.2.

The question might arise as to why we have not used supercomputers or decomposition algorithms for obtaining exact solutions for our stochastic multi-echelon LA problems. The answer is before developing the LM and ELM, we ran our problems on the Atlantic Computational Excellence Network (ACENET); unfortunately due to the problem's complexity none of them reached optimality, even after few days. Due to this I became more familiar with some limitations of the supercomputers, the fastest computers in their era. For the interested readers, some of these limitations are:

1. Some problems exist that cannot be solved faster by parallel computing;
2. There are different types of supercomputers available currently; selecting the appropriate one for any given problem needs preparation of proper guidance for the users;
3. Any run on the supercomputers often generates a huge amount of outputs which

require storage, visualization and transmission;

4. Supercomputers are often shared by several researchers, which limits the access to them.

For further information on supercomputers, one may see Banerjee (1988) and National Research Council (2005).

Additionally, we applied L-shaped decomposition algorithm, introduced by Birge and Louveaux (1997), as another option of dealing with our problems. Unfortunately it couldn't solve even a single instance to optimality in less than a day. Therefore, we propose the LM and ELM, which provide exact solutions in a reasonable time; none of the instance's computational time exceeded 11 seconds.

1.7 Contributions and Outline

This thesis aims to study the SPSCs created due to US government policies (for further details on policies see Section 1.4.2):

- Renewable Fuel Standard 2 (RFS2) – The Energy Independence and Security Act (EISA) includes RFS2, established in 2007. According to RFS2 the obligated parties, meaning gasoline refiners and gasoline importers in the US, are supposed to blend a minimum amount of bioethanol (McPhail et al. 2011; Cornell Law School 2010), called Renewable Volume Obligation (RVO) or mandate, with their gasoline each year (Thompson et al. 2009; Duffield et al. 2008). The RFS2 categorizes the bioethanol into: (1) 1^{st} generation bioethanol with 20% Greenhouse Gas (GHG) emission reduction, e.g., bioethanol produced from corn; (2) 2^{nd} generation bioethanol with 60% GHG emission reduction, e.g., bioethanol produced from corn stover; and (3) 3^{rd} generation bioethanol with 50% GHG emission reduction, e.g., bioethanol produced from algae (Baeyens et al. 2015; Thompson et al. 2009). The 1^{st} generation is long established and commercialized, the 2^{nd} generation is recently commercialized, and 3^{rd} generation yet to be commercialized. Therefore, we focus on the 1^{st} and 2^{nd} generation bioethanol in this thesis.

- Tax Credit – The Volumetric Ethanol Excise Tax Credit (VEETC) was created by the America Job Act in 2004, to motivate blending more bioethanol with gasoline. The blenders gain 0.45 $\frac{\$}{\text{gal}}$ of bioethanol blended with gasoline (McPhail et al. 2011);

- Tariff – To encourage production and blending US bioethanol with gasoline, 0.54 $\frac{\$}{\text{gal}}$ tariff for blending foreign bioethanol with gasoline was considered (McPhail et al. 2011). It is notable that the tariff for blending US bioethanol with gasoline is quite important for shifting the bioethanol production toward current critical issues, for example, diverting ethanol[2] for production of sanitizers to prevent the spread of pandemic Coronavirus Disease (COVID-19) (Voegele 2020a);

- Blend Wall (BW) – The highest amount of bioethanol (e.g., 10%) blended with each gallon of gasoline to be used in all gasoline engine vehicles is called Blend Wall (BW) (Renewable Fuels Association 2015). Under the US Clean Air Act 1963 (CAA), all gasoline engine vehicles are allowed to use up to 10% bioethanol blend with gasoline (referred to as E10); however, Flex-Fuel Vehicles (FFVs) are permitted to use up to 85% bioethanol blend with gasoline. Certain intermediate blends, e.g. 15% bioethanol blended with gasoline (E15), can be produced under certain circumstances by waiving the CAA. The E15 can be used by vehicle models manufactured later than 2000. Currently, the BW is 10% and, in general, E10 is the only gasoline consumed in the US (Yacobucci 2010).

[2] we reference ethanol as an ingredient in sanitizers, which requires a higher grade of alcohol relative to bioethanol as a fuel additive.

To that end, we fill all the research gaps in the existing literature mentioned in Section 1.5. This has formed the coming six chapters of this thesis, made up of our six papers.

Chapters 2, 3, and 4 deal with creating the most environmentally friendly SPSC, which can be employed for the 23 states that do not have any bio-refinery in place at the moment, with least challenges. Chapters 5, 6, and 7 focus on the SPSC in the 27 states with already existing facilities.

In Chapter 2, we develop a two-stage stochastic programming model, called General Model (GM), for the creation of the SPSC. The model considers 2^{nd} generation bioethanol. The GM, like any other GMs in the literature, is NP-hard in the strong sense, therefore, we develop a Lean Model (LM) to overcome the computational complexity. Then we prove relationships between solutions to both the GM and the LM. We apply the LM to run a computational experiment, consisting of 22,050 policy scenarios, in Chapter 3. Chapter 4 converts the risk neutral model in Chapter 2 to a risk averse model, quite appropriate for economic crises, by employing Conditional Value-at-Risk (CVaR); then we perform a case study. Chapter 5 extends the model in Chapter 2, by including all existing infrastructures, 1^{st} and 2^{nd} generation bioethanol, and their imports and exports. We develop the Extended General Model (EGM), and the Extended Lean Model (ELM), and prove the relationships between solutions to them. The ELM is employed to run a computational experiment, including 21,420 alternative policy scenarios, in Chapter 6. We employ the CVaR and change the risk neutral model in Chapter 5 to a risk averse model and perform a case study, in Chapter 7. Given the significance of sustainability, we report and analyze our results within its framework. We study the economic, environmental, and social aspects of the SPSC, all the case study results, more particularly policy impacts and policy recommendations, in Chapters 3, 4, 6, and 7; and provide robust strategic investment decisions despite inevitable policy changes. In Chapters 4 and 7 the results of the risk averse models are respectively compared with the corresponding risk neutral models in Chapters 3 and 6, to further clarify their significance and provide resilient strategic investment decisions in different economic conditions. Finally, in Chapter 8 we conclude our findings briefly, although readers can refer the corresponding section in each chapter, or paper, for detailed information.

The following chapter is:

Ghahremanlou, D. and W. Kubiak (2020a). Impact of government policies on Sustainable Petroleum Supply Chain (SPSC): A case study - Part I (Models). *Decision Making in Manufacturing and Services*. **In Press**.

Chapter 2

Impact of government policies on Sustainable Petroleum Supply Chain (SPSC): A case study – Part I (Models)

Abstract Environmental concerns and energy security have led governments to establish legislations to convert Conventional Petroleum Supply Chains (CPSCs) to Sustainable Petroleum Supply Chains (SPSCs). The United States (US), one of the biggest oil consumers in the world, has created regulations to manage ethanol production and consumption for the last half century. Though these regulations have created new opportunities, they have also added new burdens to the obligated parties. It is thus key for the government, the obligated parties, and related businesses to study the impact of the policies on the SPSC. We develop a two-stage stochastic programming model, General Model (GM), which incorporates Renewable Fuel Standard 2 (RFS2), Tax Credits, Tariffs, and Blend Wall (BW), to study the policy impact on the SPSC using cellulosic ethanol. The model, as any other general model available in the literature, makes it highly impractical to study the policy impact due to the model's computational complexity. We use the GM to derive a Lean Model

(LM) to study the impact by running computational experiments more efficiently and consequently arriving at robust managerial insights much faster. We present a case study of the policy impact on the SPSC in the State of Nebraska using the LM in the accompanying part II (Ghahremanlou and Kubiak 2020d).

2.1 Introduction

2.1.1 Context and Motivation

Crude oil is the main global source of vehicle transportation fuel (U.S. Energy Information Administration 2015; Kessel 2000). Global warming, uneven distribution of worldwide crude oil reservoirs, and political instability of the countries owning almost half of the known reservoirs compelled many countries to move towards local renewable energy sources (Sahebi et al. 2014b; Agarwal 2007; Yan 2012). Ethanol produced from biological materials is considered a replacement for gasoline (El-Naggar et al. 2014; Humbird et al. 2011; Baeyens et al. 2015). However, due to market restrictions and infrastructure compatibility ethanol is currently used mainly as an additive to gasoline in most countries (Agarwal 2007; Yacobucci 2010; IHS Markit 2019). The Ethanol Supply Chain (ESC) is often merged with the CPSC in its downstream, where ethanol gets blended with gasoline. The US was the biggest oil producer and consumer in 2016, and gasoline made up to 60% of total transportation fuel demand in the US. Environmental concerns and energy security led the US government to establish policies to stimulate ethanol production and consumption as an additive to gasoline. The Volumetric Ethanol Excise Tax Credit (VEETC) was created by the America Job Act in 2004, and its amount was reduced in 2009. Based on this tax credit, blenders received 0.45 $\frac{\$}{\text{gal}}$ of ethanol blended with gasoline; since imported ethanol was eligible for this credit it was subject to a 0.54 $\frac{\$}{\text{gal}}$ tariff (McPhail et al. 2011). These rules expired in 2011.

The Energy Independence and Security Act (EISA) was established in 2007. It determines the Renewable Fuel Standard 2 (RFS2). The RFS2 requires gasoline refiners and gasoline importers in the US, called obligated parties (Cornell Law School 2010; McPhail et al. 2011), to blend at least a minimum amount of renewable fuels, referred to as Renewable Volume Obligations (RVOs), or *mandate*, with their gasoline annually (Duffield et al. 2008; Thompson et al. 2009). According to RFS2, the biofuels are categorized based on their feedstock types and lifecycle Greenhouse Gas (GHG) emissions reduction (Thompson et al. 2009). The ethanol can be produced from different types of feedstocks such as corn, sugar (called first generation), with 20% GHG emission reduction; corn stover, straw (called second generation or cellulosic), with 60% GHG emission reduction; and algae (called third generation), with 50% GHG emission reduction (Baeyens et al. 2015). Based on the nested structure of RFS2, the fuels with higher emissions reduction can be used to meet the mandate for lower reduction categories (U.S. Environmental Protection Agency 2017c). The first generation biofuel production is limited in order to maintain the food security (Sharma et al. 2013), and the third generation is still under research and development, and not yet commercialized (Baeyens et al. 2015). Hence, the second generation has received considerable attention from different entities like governments and investors (Gupta and Verma 2015). According to RFS2, the mandate to blend cellulosic ethanol began in 2016 which means the obligated parties *must* comply with it. Therefore, there clearly has been a need for local cellulosic ethanol production or cellulosic ethanol import. Also, since ethanol gets easily contaminated by water, investment in the infrastructure is required for its storage and blending with gasoline.

Apart from the aforementioned incentives and obligations for blending more ethanol with gasoline, there is another control factor limiting the amount of ethanol blended. According to the US Clean Air Act 1963 (CAA), all gasoline engine vehicles are permitted to use up to 10% ethanol blended with gasoline (the E10 blend); however, Flex-Fuel Vehicles (FFVs) are allowed to use up to 85% blend (E85). The maximum amount of ethanol (e.g., 10%) which can be blended with each gallon of gasoline to be used in all gasoline engine vehicles is called Blend Wall (BW) (Renewable Fuels Association 2015). Other intermediate blends, e.g., 15% blend (E15), can be produced by waiving the CAA under certain conditions. For instance, consumption of the E15 fuel for vehicles model year 2001 and later was allowed by the US Environmental Protection Agency in 2011. Nevertheless, almost all fuel distributed in the US is E10, though ethanol producers are interested in increasing the BW to 15% (Yacobucci 2010).

Twentieth century wars arose predominately because of the desire to control and exploit oil resources (Heinberg 2005). In this century, the US lost over half million people in the wars (Hedges 2003). Recently, the Oil War between Saudi Arabia and Russia resulted in the price of US oil become negative for the first time in history, and could result in bankruptcy of hundreds of US oil companies (Blas J., S. El Wardany, G. Smith 2020; Egan and CNN Business 2020). This led to the shutdown of bio-refineries due to cheaper price for oil relative to ethanol (Almeida I., F. Batista, M. Hirtzer 2020). The combination of the Oil War and coronavirus disease (COVID-19) may have very negative impact on the US economy. The important role of US government policies for leading the situation is emphasized by Ruppert (2009). However, if policies are not well planned and communicated they might have negative impacts. For example, Philadelphia Energy Solutions, the largest U.S. East Coast oil refinery, went bankrupt in 2018. The bankruptcy resulted in job loses and calls for the amendment of some laws (Renshaw 2018; Willette 2018). The company blamed the RFS2 for the bankruptcy (DiNapoli and Renshaw 2018; Simeone 2018; Stein 2018). All of these examples provide further motivation for us to address the following questions with clear applications for production systems:

- What is the impact of the government policies: Renewable Fuel Standard 2 (RFS2), Tax Credit for Local ethanol blended with gasoline (TCL), Tax Credit for Imported ethanol blended with gasoline (TCI), Tariff for Local ethanol blended with gasoline (TL), Tariff for Imported ethanol blended with gasoline (TI), and Blend Wall (BW), on the SPSCs from the economic, social, and environmental points of view?

- How to determine the most robust decisions that are resilient to the policy change, location and production capacities for bio-refineries and blending sites in the SPSCs?

Addressing these questions will (1) shed light on how the US government may change the policies to create the SPSCs expected to achieve highest profit, most positive social impact, and most environmentally friendly fuel, with a minimum expenditure from its budget; (2) provide managerial insights to the SPSC investors on how to mitigate the chance of bankruptcy due to policy change by creating the most robust SPSCs. To our knowledge these questions have not been addressed directly in the existing literature, however, there has been substantial literature published already on various aspects of the SPSC. We review this literature in the following subsection, then summarize the contributions of this paper, and outline the paper's content.

2.1.2 Literature Review and Gaps

The government policies were studied from the economic perspective, not the supply chain perspective as in this paper, by Whistance et al. (2016), Qiu et al. (2014), Aguilar et al. (2015), Thompson et al. (2009), and Babcock (2012). Whistance et al. (2016) study the impact of RIN price information on petroleum, biofuel, and agricultural commodity markets. Qiu et al. (2014) recommend directing the government policies towards increasing the demand for E85. Aguilar et al. (2015) argue that the majority of Americans are willing to purchase fuel with a higher amount of ethanol blend, e.g., E85. Thompson et al. (2009)

employ a demand and supply curve to show under which conditions the RFS2 mandate is binding. The study done by Babcock (2012) shows that increasing RFS2, TCL, and TI increases the US corn price. While all these studies are policy related, none of them address the impact of government policies on SPSCs, and contrary to this paper, none utilize optimization methods.

The CPSCs and ESCs have been the subjects of a number of recent reviews. In particular, Sahebi et al. (2014b) and Lima et al. (2016) review research on the CPSCs. Both reviews emphasize the study of real-life CPSCs, new incentive schemes, and development of efficient algorithms for solving real-life CPSC optimization problems as the most promising research avenues to pursue. Mafakheri and Nasiri (2014) and Ghaderi et al. (2016) review literature on Biofuel Supply Chains (BSCs), which include the ESCs, and they underline the importance of incorporating government policies in the models of the BSCs. Ghaderi et al. (2016) argue that conducting case studies of BSCs in regions with different climates, economic and political situations are new directions for further research. Ba et al. (2016) review biomass supply chains which are parts of BSCs. Their findings show the need for optimization and efficient algorithms for large biomass supply chains which clearly apply to the SPSCs. Chukwuma (2019) advocates integration of GIS data in the mathematical programming models. Our research is aimed at filling in the gaps identified by these publications by addressing the issue of developing an efficient optimization algorithm and a real-life case study presented in the accompanying part II (Ghahremanlou and Kubiak 2020d) for the state of Nebraska, which has not been studied from the SPSC point of view, using available real-life data, and GIS data in particular.

In order to convert a CPSC to an SPSC gasoline can be blended either with ethanol or with drop-in biofuel (i.e. biofuel compatible with the existing infrastructure) (Yue et al. 2014). Tong, You, and Rong (2014), Tong et al. (2013), and Tong, Gleeson, Rong, and You (2014) study design and operation of the SPSC with drop-in biofuel; Najmi et al. (2016) focus on the equilibrium models for the SPSC with drop-in biofuel. However, currently the drop-in biofuel is not being used in the US, and it is still often referred to as an energy for the future (U.S. Department of Energy 2013). Therefore, in this paper we focus on the SPSC which is created by merging an ESC with a CPSC. Andersen et al. (2013) and Kazemzadeh and Hu (2015) study such SPSCs. Andersen et al. (2013) propose a strategic model to investigate the regions of the US which require investment to implement the SPSC. They also propose a detailed model to study distribution of fuel within a state. Their models focus on cost minimization, do not include uncertainty which is present in the ESCs (Awudu and Zhang 2012; Meyer 2007; Yue et al. 2014), and do not consider ethanol imports. Kazemzadeh and Hu (2015) incorporate RFS2 and TCL in their stochastic programming model which does not, however, consider ethanol imported into the US. They run their computational experiments for 9 instances yet they do not report on whether they were able to find optimal solutions for those instances in reasonable time. Their research again underlines the need for new models that both provide solutions for a large number of instances in reasonable time and provide key insights into the policy through those solutions. This paper aims to fill the gaps by including uncertain factors, imported ethanol from other states and abroad, and a broader range of policies in the proposed models.

The SPSC needs to establish bio-refineries in some locations to process a limited supply of corn stover. The ethanol produced in those bio-refineries may be exported or shipped out to blending sites which also need to be established in some locations for blending ethanol with gasoline and for storage. Finally, the fuel (blend) is shipped out from blending sites to distribution centers to meet demand for fuel. From that perspective the creation of the SPSC requires solving a Multi-echelon Location-Allocation (LA) problem (Cooper 1963; Wang and Lee 2015; Shankar et al. 2013). The LA problem is also key to applications in many other operation research (OR) areas, e.g., healthcare (Mestre et al. 2015), and energy (Chukwuma 2019; Chen and Fan 2012; Gebreslassie et al. 2012b; Liu et al. 2010; Serrano-

Hernandez et al. 2017). Azarmand and Neishabouri (2009) provide a classification of the LA problems.

The LA problem, even deterministic and single-echelon, is NP-hard. Due to the computational complexity of the LA problem the instances with large numbers of potential locations cannot be solved to optimality in reasonable time by standard solvers like Gurobi. Moreover, though some customized algorithms like a branch and bound algorithm of Kuenne and Soland (1972) have been proposed in the literature it remains to be seen whether they can even compete with off-the-shelf optimization solvers, e.g., Gurobi. Therefore, the optimal solutions for the instances with large numbers of potential locations are out of reach in practice, and thus various heuristics have been proposed in the literature (Murray and Church 1996; Bischoff and Dächert 2009). The computational complexity grows further if the uncertainty is introduced in LA problems which is the case for this paper. To provide the reader with a perspective it is worth pointing out that Chen and Fan (2012) employ the Progressive Hedging (PH) algorithm for solving a stochastic programming model with 8 scenarios, but they only reach a solution within 0.131% from the optimum after 2 hours, though without proving that the solution is optimal. Clearly showing that the solution found may be relatively close to the optimum (more precisely to either a lower or an upper bound obtained by relaxations) in reasonable time does not mean that the optimum itself can also be found in reasonable time since the proof of optimality is typically much more time consuming due to the problem NP-hardness. The computational complexity poses a formidable barrier in policy impact analysis based on optimization since the analysis requires a large number of instances to be solved to optimality. This paper proposes a lean model to overcome this barrier.

2.1.3 Paper Contributions and Outline

We identified a number of gaps in the existing literature in the previous subsection. Those gaps will be filled in by our contributions that we briefly describe in this subsection, leaving their details for the remaining sections and to the accompanying part II (Ghahremanlou and Kubiak 2020d).

This paper studies the impact of the US government policies concerning cellulosic ethanol (RFS2, TCL, TCI, TL, TI, and BW) on the SPSC. We call a six-tuple (RFS2, TCL, TCI, TL, TI, BW) of values for each RFS2, TCL, TCI, TL, TI, and BW a policy combination or just a policy. This requires *multiple* instances, thousands in this study, obtained by changing the values of mandate (RFS2), tax credits (TCL and TCI), tariffs (TL and TI), and blend wall (BW), to be solved to optimality efficiently in computational experiments. That task is impossible at the moment for the General Model (GM) based on two-stage stochastic programming presented in this paper, and also for any other similar model presented in the literature. This becomes clear from the literature review showing that solving multi-echelon location-allocation stochastic programs to optimality is practically beyond reach even for a *single* real-life instance with close to a hundred potential locations. Therefore, in this paper we propose a Lean Model (LM) based on two-stage stochastic programming to study the impact. The LM proposes a macro level view on the flows of corn stover, ethanol and fuel which significantly reduces time required by computational experiments. We prove key relationships between optimal solutions to the GM and the LM, which help in making more robust decisions.

The rest of the paper is organized as follows: Section 2.2 informally describes the problem; Section 2.3 gives mathematical programming formulation of two models of the problem. Section 2.3.1 formulates the General Model (GM) as a two-stage stochastic programming model. The notations, including variables and parameters, for the formulation are defined in Appendix 2.5.1. Section 2.3.2 gives the formulation of a Lean Model (LM) which aggregates the flow variables of the GM. The aggregated variables are defined in Appendix 2.5.2.

2.2 Problem Statement

The problem consists of establishing an SPSC in a state of the US to meet that area's demand for fuel (ethanol-gasoline blend) in such a way that the annual expected profit is maximized. The investment in the SPSC has been accelerated by the market created by the RFS2 mandate. Here we assume the investors take the lead to create what is required to convert a CPSC to the SPSC according to the legislations. They also manage the SPSC. The design and operation of the SPSC are subject to various regulations: RFS2, TCL, TCI, TI, TL, and BW. The impact of these regulations on the SPSC is the main focus of this paper.

The SPSC includes harvesting sites, bio-refineries, blending sites, ethanol exporters, ethanol importers from other states and abroad, refineries, gasoline importers, and distribution centers (Figure 4.1). Each county of the state has its own harvesting site and distribution center both located in the center of the county. The harvesting sites and distribution centers have their own amounts of feedstock and fuel demand respectively. Furthermore, the center of each county is a potential location for bio-refineries and blending sites. These are established by a US government loan which will be repaid during t years with an interest rate ϕ. Therefore, the problem resembles a project management type of problem which requires network design within a limited budget, where initially, the facilities locations (bio-refineries, and blending sites) are decided, and then the flows (of feedstock, ethanol, and fuel) are determined. The bio-refineries and blending sites have the same technology but different capacities and, accordingly, different costs to establish.

The feedstock is purchased from farmers. To keep the land fertile, only a specific portion of feedstock available can be considered for shipping to the bio-refineries; out of this amount a portion is lost due to baling and loading. The transportation network for feedstock depends on the location of bio-refineries. Bio-refineries convert a specific portion of the feedstock to ethanol which can then be shipped to blending sites and/or sold to ethanol exporters. The transportation network for ethanol depends on the location of bio-refineries and blending sites. Blending sites receive ethanol from bio-refineries, other states, and abroad, and gasoline from refineries, and other countries, and blend the two according to the BW. The imported ethanol (from other states and abroad) and gasoline (from refineries and other countries) are purchased to be delivered to blending site locations. The fuel is shipped to distribution centers to be sold to the customers. The transportation network for the fuel depends on the location of blending sites. The transportation of materials (feedstock, ethanol, and fuel) includes distance-fixed cost and distance-variable cost, and it is done by truck. We incorporate all regulations: RFS2, TCL, TCI, TI, TL, and BW in the model.

The uncertain factors in the model are: feedstock availability, feedstock price, variable transportation cost, ethanol import prices, fuel price, gasoline price, ethanol exporting price, fuel demand, number of jobs created due to different activities (construction of bio-refineries and blending sites, feedstock to ethanol conversion and ethanol-gasoline blending operations, and transportation of feedstock, ethanol and fuel).

We consider two objectives: the main objective is maximization of the annual expected profit, and the secondary is maximization of the expected number of jobs created in the state within the project lifetime of Q years. We assume the jobs are created only for construction of bio-refineries and blending sites, their operations (feedstock to ethanol conversion, and ethanol-gasoline blending), and transportation (feedstock, ethanol, and fuel).

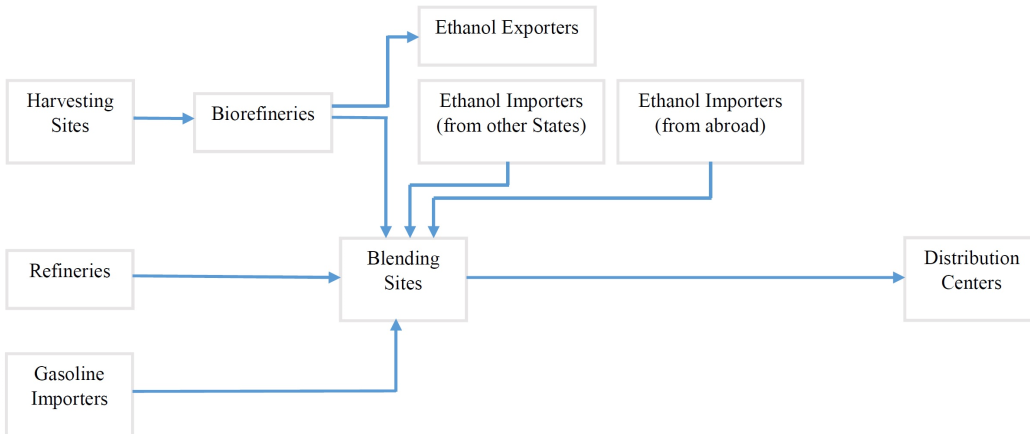


Figure 2.1: Sustainable Petroleum Supply Chain Network

2.3 Formulation of Models

In this section two types of mathematical programming models are explained. The first one is the GM which includes the details. The second one is the LM which is a conceptual model based on the GM.

2.3.1 General Model (GM)

We develop a two-stage stochastic programming model for the problem in this section. At the first stage the decisions regarding the locations and capacities of bio-refineries and blending sites are made before the realization of uncertain factors. At the second stage all the uncertain factors are realized and then the flow decisions are made. Therefore, the flow decisions are optimal.

The design constraints are formulated in subsection 2.3.1.1, the flow constraints are given in subsection 2.3.1.2, finally the objective functions are formulated in the subsections 2.3.1.3, 2.3.1.4, and 2.3.1.5. To streamline the presentation we leave quite heavy notations required by the variables and the parameters of the model to Appendix 2.5.1. The model needs to handle three different types of facilities: bio-refineries, blending sites, and distribution centers; and the flows of three different products: corn stover, ethanol, and fuel. To facilitate the presentation of the model we adopt the convention represented by the following upstream-downstream path (harvesting site j) $\rightarrow$ (bio-refinery i) $\rightarrow$ (blending site j) $\rightarrow$ (distribution center i). That is, corn stover flows from j to i, thus f_{jis} in scenario s, ethanol flows from i to j, thus e_{ijs} in scenario s, and fuel flows from j to i, thus x_{jis} in scenario s. Consequently, for instance, we use the notation d_{ji} for the distance between the harvesting site in county j and bio-refinery in county i, while d_{ij} for the distance between bio-refinery in county i and blending site in county j.

2.3.1.1 Design Constraints

The design constraints are related to the locations and capacities of bio-refineries and blending sites. The constraint (2.1) guarantees that the total investment in the construction of bio-refineries and blending sites in the state does not exceed B, the available budget. The constraints (2.2) and (2.3) guarantee that at most one bio-refinery and at most one blending site, respectively, become established in each county of the state.

$$\sum_m C_m \cdot \sum_i r_{mi} + \sum_n W_n \cdot \sum_j b_{nj} \leq B \tag{2.1}$$

$$\sum_m r_{mi} \leq 1, \qquad \forall i \in N \tag{2.2}$$

$$\sum_n b_{nj} \leq 1, \qquad \forall j \in N. \tag{2.3}$$

2.3.1.2 Flow Constraints

Suppose the production of ethanol takes place in the state. This will generate three types of flows between the counties of the state: the flow of *feedstock*, the flow of *ethanol*, and the flow of *fuel*. In this section, constraints about the flows are introduced and discussed.

The out-flow of feedstock from each county j must not exceed the amount of feedstock available for shipping from that county. This amount depends on the sustainability factor (F), and the feedstock loss factor (L). These two factors are considered the same for all counties, as all the counties are located in one state, and the collection, baling, and loading method is the same. Therefore, the left-hand side of the constraint (2.4) shows total feedstock available for shipping from county j in scenario s, and the right-hand side shows the out-flow of feedstock from j in scenario s.

$$(1-L)\cdot\left[(1-F)\cdot A_{js}\right] \geq \sum_i f_{jis}, \qquad \forall j \in N, \forall s \in S \tag{2.4}$$

The in-flow of feedstock to county i must not exceed the bio-refinery capacity in county i in scenario s which is guaranteed by (2.5). In particular this constraint guarantees that the feedstock does not flow from any other county j to i without a bio-refinery in any scenario s.

$$\sum_j f_{jis} \leq \sum_m U_m \cdot r_{mi}, \qquad \forall i \in N, \forall s \in S \tag{2.5}$$

The percentage V of all feedstock available to the bio-refinery located in county i is converted to ethanol, the left-hand side of (2.6). This amount of ethanol either flows from i to the counties of the state (possibly including i) with blending sites or it is sold to the exporters (o_{is}), by county i in scenario s, the right-hand side. Observe that this constraint along with (2.5) guarantees that ethanol flow out of a county without a bio-refinery is forbidden.

$$V\cdot\sum_j f_{jis} = \sum_j e_{ijs} + o_{is}, \qquad \forall i \in N, \forall s \in S \tag{2.6}$$

The in-flow of ethanol to county j must not exceed the capacity of the blending site established in county j in scenario s which is guaranteed by (2.7). In particular this constraint guarantees no ethanol, either from the bio-refinery located in county i or purchased from other states or abroad, flows to j without a blending site in any scenario s.

$$\left[\sum_i e_{ijs} + h_{js} + k_{js} + g_{js}\right] \leq \sum_n H_n \cdot b_{nj}, \qquad \forall j \in N, \forall s \in S \tag{2.7}$$

The total amount of ethanol that flows into a blending site in county j must not exceed the fraction α, the BW, of the total in-flow, ethanol and gasoline, into the blending site. This is guaranteed by (2.8).

$$\left[\sum_i e_{ijs} + h_{js} + k_{js}\right] \leq \alpha \cdot \left[\sum_i e_{ijs} + h_{js} + k_{js} + g_{js}\right], \qquad \forall j \in N, \forall s \in S \tag{2.8}$$

The following constraint (2.9) guarantees that the total amount of ethanol purchased annually from other states ($\sum_j h_{js}$) will not exceed their total annual ethanol production capacity (E) in any scenario s.

$$\sum_j h_{js} \leq E, \qquad \forall s \in S \tag{2.9}$$

Finally consider the fuel flows. The left-hand side of the constraint (2.10) equals the total amount of fuel blended by the blending site located in county j in scenario s. The right-hand side of the constraint equals the total out-flow of fuel from j to the distribution centers of counties (including j) in scenario s.

$$\left[\sum_i e_{ijs} + h_{js} + k_{js} + g_{js}\right] = \sum_i x_{jis}, \qquad \forall j \in N, \forall s \in S \tag{2.10}$$

The in-flow of fuel to the distribution center in county i must meet demand for fuel in i in scenario s. This is guaranteed by (2.11).

$$\sum_j x_{jis} = D_{is}, \qquad \forall i \in N, \forall s \in S \tag{2.11}$$

It is worth observing that the constraints of the model, in particular the constraints (2.8), (2.10), and (2.11), do not guarantee that a feasible solution requires any positive amount of ethanol to be produced. Thus some feasible solutions may not require any production of ethanol. It would however be the mandate's task to impose the penalty on the obligated parties in order to provide the incentive for investors to produce ethanol and to establish bio-refineries and blending sites in the state. Therefore the mandate would make the solutions which do not require ethanol production to be unlikely candidates for optimal solutions. The mandate is discussed next.

2.3.1.3 The Mandate

The mandate is calculated as a fraction of total gasoline consumption ($\sum_j g_{js}$) in the state. The fraction is determined by the current renewable standards $\overline{R}$ and $\overline{\overline{R}}$ for the first and the second generation ethanol respectively. The mandate has been waived or changed by the government due to hitting the BW or to immaturity of the conversion technologies by adjusting the standards $\overline{R}$ and $\overline{\overline{R}}$. Since the conversion technology for the first generation ethanol has been completely developed and matured, which is not the case for the second generation, we use coefficient β for $\overline{\overline{R}}$. Due to the nested structure of the RFS2 regulations the total coefficient $\overline{R} + \beta \cdot \overline{\overline{R}}$ may apply to the second generation ethanol only. Thus the mandate is defined as follows:

$$M_s := \left[\overline{R} + \beta \cdot \overline{\overline{R}}\right] \cdot \sum_j g_{js}, \qquad \forall s \in S \tag{2.12}$$

The mandate is met by having enough Renewable Identification Numbers (RINs). One gallon ethanol is counted as one RIN. The RINs are detached when ethanol is blended with gasoline. The number of detached RINs compared to the mandate will have one of these three outcomes: (1) the number of RINs equals the mandate; (2) the number of RINs is less than the mandate and the deficiency must be purchased from other obliged parties; (3) the number of RINs is greater than the mandate and the surplus is sold to other obliged parties. We define a variable RIN_s as the deviation of the amount of ethanol blended with gasoline from the mandate.

$$RIN_s := \left[\sum_i \sum_j e_{ijs} + \sum_j h_{js} + \sum_j k_{js}\right] - M_s, \qquad \forall s \in S \tag{2.13}$$

This variable is part of the objective function we define in the next section, its contribution to the value of the objective could be zero, negative, or positive depending on the outcome (1), (2) or (3) respectively.

2.3.1.4 Expected Profit Maximization Objective Function

The primary objective function maximizes annual expected profit. It includes expected revenues and expected costs. The expected revenues are as follows:

- The revenue from selling extra RINs (if $RIN_s > 0$), or the cost of purchasing the deficiency (if $RIN_s < 0$)

$$R^R = P^R \cdot \sum_s RIN_s \cdot \omega_s \tag{2.14}$$

  where P^R is the RIN price, RIN_s is the number of RINs in scenario s defined in (2.13), and ω_s as the probability of scenario s. The mandate's task is to impose the penalty reflected in (2.12), (2.13), and (2.14) on the obligated parties in order to provide the incentive for investors to produce ethanol and to establish bio-refineries and blending sites in the state.

- The revenue from selling fuel

$$R^S = \sum_s P_s \cdot \omega_s \cdot \sum_i D_{is} \tag{2.15}$$

  where P_s is the fuel market price in scenario s. Observe that the revenue does not depend on any variable of the model, however it does depend on fuel demand in the state.

- The revenue generated by TCL (R^{TL}) includes two parts: one represents the ethanol produced in the state ($\sum_i \sum_j e_{ijs}$), while the other one is the ethanol imported from other states ($\sum_j h_{js}$) in scenario s. The Tax Credit per gallon of the US ethanol equals T, and η is a coefficient to take care of the government decisions to change the TCL. When $\eta < 0$, R^{TL} becomes the TL.

$$R^{TL} = \eta \cdot T \cdot \left[\sum_s \omega_s \cdot \sum_i \sum_j e_{ijs} + \sum_s \omega_s \cdot \sum_j h_{js} \right] \tag{2.16}$$

- The revenue generated by TCI (R^{TC}) depends on the amount of ethanol imported from other countries ($\sum_j k_{js}$) in scenario s. The government may decide to change the Tax Credit per gallon of foreign ethanol $\overline{T}$, and thus we consider coefficient θ to take care of this change. When $\theta < 0$, R^{TC} becomes the TI.

$$R^{TC} = \theta \cdot \overline{T} \cdot \sum_s \omega_s \cdot \sum_j k_{js} \tag{2.17}$$

- The revenue generated by selling the ethanol produced by bio-refineries to the exporters is R^{EE}. The amount of the ethanol sold equals $\sum_i o_{is}$, and the selling price P_s^E per gallon in scenario s.

$$R^{EE} = \sum_s P_s^E \cdot \omega_s \cdot \sum_i o_{is} \tag{2.18}$$

The expected costs are as follows:

- This annual loan payment with an interest rate ϕ will be continued for t years.

$$C^A = \left[\frac{\phi \cdot (1+\phi)^t}{(1+\phi)^t - 1}\right] \cdot \left[\sum_m C_m \cdot \sum_i r_{mi} + \sum_n W_n \cdot \sum_j b_{nj}\right] \tag{2.19}$$

- The cost of purchasing feedstock

$$C^{FP} = \sum_s P_s^F \cdot \omega_s \cdot \sum_j \sum_i f_{jis} \tag{2.20}$$

where $\sum_j \sum_i f_{jis}$ is the total amount of feedstock shipped from harvesting sites to bio-refineries and P_s^F is price per ton (MT).

- The operating costs

$$C^O = C^{FE} \cdot \sum_s \omega_s \cdot \sum_i (o_{is} + \sum_j e_{ijs}) + C^B \cdot \sum_s \omega_s \cdot \sum_i D_{is} \tag{2.21}$$

include the costs of conversion of feedstock into ethanol at bio-refineries, and costs of blending ethanol and gasoline at blending sites. The former depends on the amount of ethanol produced in the state ($\sum_i(\sum_j e_{ijs} + o_{is})$), the latter on the fuel demand ($\sum_i D_{is}$) in the state in scenario s.

- The transportation cost of feedstock C^{TF}, ethanol C^{TE}, and fuel C^{TEG}

$$C^{TF} = C^{FTF} \cdot \sum_s \omega_s \cdot \sum_j \sum_i f_{jis} + \tau \cdot \sum_s C_s^{VTF} \cdot \omega_s \cdot \sum_j \sum_i f_{jis} \cdot d_{ji} \tag{2.22}$$

$$C^{TE} = C^{FTE} \cdot \sum_s \omega_s \cdot \sum_j \sum_i e_{ijs} + \tau \cdot \sum_s C_s^{VTE} \cdot \omega_s \cdot \sum_j \sum_i e_{ijs} \cdot d_{ij} \tag{2.23}$$

$$C^{TEG} = C^{FTEG} \cdot \sum_s \omega_s \cdot \sum_j \sum_i x_{jis} + \tau \cdot \sum_s C_s^{VTEG} \cdot \omega_s \cdot \sum_j \sum_i x_{jis} \cdot d_{ji} \tag{2.24}$$

are calculated using fixed unit costs C^{FTF}, C^{FTE}, and C^{FTEG} respectively, and variable unit cost C_s^{VTF}, C_s^{VTE}, and C_s^{VTEG} respectively. To better approximate distances d_{ji} between the counties of the state the tortuosity factor (τ) is included in the calculations.

- The cost of importing ethanol

$$C^I = \sum_s P_s^{EI} \cdot \omega_s \cdot \sum_j h_{js} + \sum_s P_s^{EE} \cdot \omega_s \cdot \sum_j k_{js} \tag{2.25}$$

purchasing $\sum_j h_{js}$ of ethanol from other states with unit cost of P_s^{EI}, and importing $\sum_j k_{js}$ of ethanol from other countries with unit cost of P_s^{EE} in scenario s.

- The cost of purchasing petroleum gasoline to blend with ethanol

$$C^G = \sum_s P_s^G \cdot \omega_s \cdot \sum_j g_{js} \tag{2.26}$$

at unit price P_s^G in scenario s.

Therefore, the primary objective function is as follows:

$$G_1 = (R^R + R^S + R^{TL} + R^{TC} + R^{EE}) - (C^A + C^{FP} + C^O + C^{TF} + C^{TE} + C^{TEG} + C^I + C^G) \tag{2.27}$$

2.3.1.5 Expected Jobs Created Maximization Objective Function

The secondary objective, maximization of the expected number of jobs created in the state during the Q years lifetime of the project, includes:

- The number of jobs created for the construction

$$J^C = \sum_s J_s^{Co} \cdot \omega_s \cdot \left[\sum_m C_m \cdot \sum_i r_{mi} + \sum_n W_n \cdot \sum_j b_{nj}\right] \tag{2.28}$$

  calculated based on the amount of the investment in the construction of bio-refineries and blending sites;

- The number of jobs created by the transportation of feedstock

$$J^{TF} = Q \cdot \tau \cdot \left[\sum_s \omega_s \cdot J_s \cdot \sum_j \sum_i f_{jis} \cdot d_{ji}\right] \tag{2.29}$$

- The number of jobs created by the transportation of ethanol

$$J^{TE} = Q \cdot \tau \cdot \left[\sum_s \omega_s \cdot J_s^{TE} \cdot \sum_i \sum_j e_{ijs} \cdot d_{ij}\right] \tag{2.30}$$

- The number of jobs created by the transportation of fuel

$$J^{TEG} = Q \cdot \tau \cdot \left[\sum_s \omega_s \cdot J_s^{TEG} \cdot \sum_j \sum_i x_{jis} \cdot d_{ji} \right] \tag{2.31}$$

- The number of jobs created by the ethanol production and blending in the state

$$J^O = Q \cdot \left[\sum_s J_s^{FE} \cdot \omega_s \cdot \sum_m \sum_i C_m \cdot r_{mi} + \sum_s J_s^B \cdot \omega_s \cdot \sum_n \sum_j W_n \cdot b_{nj} \right]. \tag{2.32}$$

The secondary objective function is as follows:

$$G_2 = J^C + J^{TF} + J^{TE} + J^{TEG} + J^O. \tag{2.33}$$

Observe from (2.33) that the secondary objective does not depend on the Renewable Fuel Standard 2 (RFS2), the Blend Wall (BW), the Tax Credit for the US produced ethanol (TCL), the Tax Credit for the foreign produced ethanol (TCI), the Tariff for the US produced ethanol (TL), or the Tariff for the Imported ethanol (TI). Thus the changes in the government policies affecting these do not affect the maximization of the secondary objective. Also, the objective is in conflict with the primary objective since the increase in the flows weighted by the distances, which may be a result of changes in bio-refineries or blending site locations, reduces the expected profit while at the same time it increases the expected number of jobs created.

2.3.2 Lean Model (LM)

The GM belongs to the class of NP-hard problems, thus its optimization is very unlikely to be done efficiently. Even the design problem itself, i.e. the decision where to locate bio-refineries and blending sites in order to minimize the transportation costs of feedstock, ethanol, and fuel is NP-hard and thus difficult to solve efficiently. Therefore, it is unlikely that a single instance of the problem could be solved efficiently, even more so when multiple instances are required to be solved to show the impact of policy change by changing the values of α, β, η and θ. This motivates us to come up with a model that captures the main features of the problem, and thus makes it relevant for strategic decision making and policy analysis, though it does so at a cost of hiding less relevant details for these purposes. We propose a LM in this section that does just that by aggregating variables over counties of the state thus hiding particular flows between them. The aggregated variables are defined in Appendix 2.5.2. The flows may be irrelevant at this project management level though the total flow obtained by the aggregation is and will be part of the LM. One could argue that replacing the GM by the LM leads to the loss of precision in determining the value of the optimal solution. However, we need to keep in mind that the parameters of the models are often estimates, see for instance the discussion of the corn stover price and conversion rate parameters in Humbird et al. (2011), or consider the fact the cellulosic ethanol production is still in the process of commercialization which explains the lack of data pertaining to its performance. The British economist John Maynard Keynes once remarked: "it is much better to be roughly right than precisely wrong" (Ortúzar and Willumsen 2011). Therefore, a general rule acceptable in model building is the fewer parameters the better. The LM is less parameter hungry than the GM since it does not require the unit transportation costs C^{TF}, C^{TE}, and C^{TEG}, and unit job rates J^{TF}, J^{TE}, and J^{TEG}. The LMs take much less time to solve by standard universal solvers like Gurobi.

2.3.2.1 Constraints

To write the LM constraints, we employ the aggregated variables, see Appendix 2.5.2 for definition, and closely mirror the constraints of the GM.

The number of bio-refineries with capacity level m, denoted by r_m, and the number of blending sites with capacity level n, denoted by b_n, to set up must not exceed the budget B. This is guaranteed by the following constraint

$$\sum_m C_m \cdot r_m + \sum_n W_n \cdot b_n \leq B \tag{2.34}$$

The constraints (2.35) and (2.36) guarantee that the number of bio-refineries and the number of blending sites do not exceed the number of counties, $|N|$, respectively.

$$\sum_m r_m \leq |N| \tag{2.35}$$

$$\sum_n b_n \leq |N| \tag{2.36}$$

The total shipments of corn stover to bio-refineries, denoted by f_s, in scenario s must not exceed the limit set by the supply of the corn stover in the state in s after factoring in the corn stover loss, L, and the sustainability, F, factors. This is guaranteed by the following constraint

$$f_s \leq A_s \cdot (1-L) \cdot (1-F), \qquad \forall s \in S \tag{2.37}$$

and they must respect the limit imposed by the total bio-refineries capacity

$$f_s \leq \sum_m U_m \cdot r_m, \qquad \forall s \in S \tag{2.38}$$

The total production of ethanol by bio-refineries, $V \cdot f_s$, in scenario s is either used in the state, e_s, or exported, o_s, which is guaranteed by the following constraint

$$V \cdot f_s = e_s + o_s, \qquad \forall s \in S \tag{2.39}$$

The ethanol available in the state in scenario s which is made up of the ethanol purchased from other states, h_s, or abroad, k_s, or produced internally in the state, e_s, must not exceed the fraction α, of the total demand for fuel in the state in s. This is guaranteed by

$$e_s + h_s + k_s \leq \alpha \cdot D_s, \qquad \forall s \in S \tag{2.40}$$

The amount of ethanol purchased from other states must not exceed the limit E

$$h_s \leq E, \qquad \forall s \in S \tag{2.41}$$

and the state demand must not exceed the blending capacity of the state which is guaranteed by

$$D_s \leq \sum_n H_n \cdot b_n, \qquad \forall s \in S \tag{2.42}$$

The next three constraints recognize that the shipments of corn stover can be split into two parts, external, the shipments between the counties, f_s^E, and internal, within the counties f_s^I, (2.43), the latter occurring only in those counties with bio-refineries

$$f_s = f_s^E + f_s^I, \qquad \forall s \in S \tag{2.43}$$

the shipments of ethanol can be split into two parts, external, the shipments between the counties, e_s^E, and internal, within the counties e_s^I, (2.44), the latter occurring only in those counties with both bio-refineries and blending sites

$$e_s = e_s^E + e_s^I, \qquad \forall s \in S \tag{2.44}$$

the shipments of fuel can be split into two parts, external, the shipments between the counties, x_s^E, and internal, within the counties x_s^I, (2.45), the latter occurring only in those counties with blending sites

$$D_s = x_s^E + x_s^I, \qquad \forall s \in S \tag{2.45}$$

The new variables introduced in (2.43-2.45) are required to better approximate the solution of the GM by the solution to the LM which can be solved more efficiently than the GM. Finally, we add constraints that upper bound the internal shipments of feedstock, ethanol, and fuel so that a disaggregation with the same flows, internal in particular, would be possible. Section 2.3.3 gives more details on this.

Define $B_{is}^m = \min\{A_{is} \cdot (1-F) \cdot (1-L), U_m\}$ for $m = 1,2,3,\ i = 1,...,|N|$, and $s \in S$. We add the following constraints

$$\sum_i r_{mi} = r_m, \qquad \forall m = 1,2,3 \tag{2.46}$$

$$\sum_m r_{mi} \leq 1, \qquad \forall i = 1,...,|N| \tag{2.47}$$

$$f_s^I \leq \sum_i \sum_m B_{is}^m \cdot r_{mi}, \qquad \forall s \in S \tag{2.48}$$

Define $C_{js}^n = \min\{D_{js}, H_n\}$ for $n = 1,...,6,\ j = 1,...,|N|$, and $s \in S$. We add the following constraints

$$\sum_j b_{nj} = b_n, \qquad \forall n = 1,...,6 \tag{2.49}$$

$$\sum_n b_{nj} \leq 1, \qquad \forall j = 1,...,|N| \tag{2.50}$$

$$x_s^I \leq \sum_j \sum_n C_{js}^n \cdot b_{nj}, \qquad \forall s \in S \tag{2.51}$$

It is worth observing that constraints (2.48) and (2.51) put upper bounds on the internal flows of corn stover and blend respectively. These bounds may not allow us to take advantage of the economy of scale implied by the strict concavity of bio-refineries and blending sites cost functions in general, cost-level$_k = k^{0.6} \cdot$ base cost for $k = 1,2,3$ (Ghahremanlou and Kubiak 2020d). The following example explains why this may happen for corn stover. Assume $U_1 = 100$, $U_2 = 200$, and the supply of corn stover, $A_i \cdot (1-F) \cdot (1-L)$, from the top corn stover supply counties are 80, 70, and 50. Now consider the following two solutions:

- $r_1 = 2, r_2 = 0, r_3 = 0$. By constraint (2.46)

$$\sum_i r_{1i} = 2, \sum_i r_{2i} = 0, \sum_i r_{3i} = 0, \tag{2.52}$$

  and by constraint (2.47)

$$r_{1i} + r_{2i} + r_{3i} \leq 1, \forall i \Rightarrow r_{1j} \leq 1, \forall i. \tag{2.53}$$

  Thus by (2.48), and $B_i^1 = \min\{A_i \cdot (1-F) \cdot (1-L), U_1 = 100\}$, we have $f_s^I \leq \sum_j \sum_m B_{is}^m \cdot r_{mi} = 150$, and clearly the internal flow of $f_s^I = 150$ is achievable by locating the two bio-refineries of capacity $U_1 = 100$ each in the two counties with the highest corn stover supplies, 80 and 70 respectively.

- $r_1 = 0, r_2 = 1, r_3 = 0$. By constraint (2.46)

$$\sum_i r_{1i} = 0, \sum_i r_{2i} = 1, \sum_i r_{3i} = 0, \tag{2.54}$$

and by constraint (2.47)

$$r_{1i} + r_{2i} + r_{3i} \leq 1, \forall j \Rightarrow r_{2i} \leq 1, \forall i. \tag{2.55}$$

Thus by (2.48), and $B_i^2 = \min\{A_i \cdot (1-F) \cdot (1-L), U_2 = 200\}$, we have $f_s^I \leq \sum_i \sum_m B_{is}^m \cdot r_{mi} = 80$, and clearly the internal flow of $f_s^I = 80$ is achievable by locating a single bio-refinery of capacity $U_2 = 200$ in the county with the highest corn stover supply, 80.

The former solution increases the cost of establishing bio-refineries by ignoring the economy of scale. However, the two bio-refineries established in two different counties permit higher internal flows. The latter solution, on the other hand, takes advantage of the economy of scale to reduce the cost of establishing bio-refineries, however, it reduces the internal flow since such flow is now limited to a single county where the bio-refinery is located. Therefore the reduction in transportation costs due to higher internal flows may outweigh the increase in the costs of establishing bio-refineries, thus the former solution may result in higher expected profit than the latter.

Define $E_{mn} = \min\{V \cdot U_m, \alpha \cdot H_n\}$ for $m = 1,2,3$, and $n = 1,...,6$. The following constraints limit the internal flow of ethanol

$$e_s^I \leq \sum_m \sum_n \sum_j E_{mn} \cdot P_{mn}^j, \qquad \forall s \in S \tag{2.56}$$

$$\sum_n P_{mn}^j \leq r_{mj}, \qquad \forall j = 1,...,|N|, \forall m = 1,2,3 \tag{2.57}$$

and

$$\sum_m P^j_{mn} \le b_{nj}, \qquad \forall j = 1, ..., |N|, \forall n = 1, ..., 6 \tag{2.58}$$

Observe that the two constraints (2.57-2.58) imply that for $P^j_{mn} = 1$ it is necessary, but not sufficient, that both a bio-refinery of size U_m and blending site of size H_n are established in j. However, in optimality, when $r_{mj} = 1$ and $b_{nj} = 1$ then $P^j_{mn} = 1$, since e^I_s will be maximized and therefore P^j_{mn} has to reach its cap.

Finally, we define

$$M_s := \left[\overline{R} + \beta \cdot \overline{\overline{R}}\right] \cdot \left[D_s - (e_s + h_s + k_s)\right], \qquad \forall s \in S \tag{2.59}$$

$$RIN_s := [e_s + h_s + k_s] - M_s, \qquad \forall s \in S \tag{2.60}$$

Observe that only one constraint, (2.40), includes α, a policy parameter out of α, β, η or θ. This constraint represents the impact of BW, α, on the space of feasible solutions. A change in α may cause change in at least one of the variables e_s, h_s and k_s. Furthermore, e_s is tied with the design variable r_m and b_n. Therefore, a change in the BW may impact the long term strategic design decisions in the SPSC.

2.3.2.2 LM Objective Functions

The following revenues, costs, and number of job components of the LM objective functions, defined in (2.61-2.78), exactly mirror those of the GM objective functions, defined in (2.14-2.26) and (2.28-2.32). The former are essentially obtained from the latter by replacing the variables of the latter by their aggregations defined in Appendix 2.5.2.

$$R^R = P^R \cdot \sum_s RIN_s \cdot \omega_s \tag{2.61}$$

$$R^S = \sum_s P_s \cdot \omega_s \cdot D_s \tag{2.62}$$

$$R^{TL} = \eta \cdot T \cdot \left[\sum_s \omega_s \cdot e_s + \sum_s \omega_s \cdot h_s\right] \tag{2.63}$$

$$R^{TC} = \theta \cdot \overline{T} \cdot \sum_s \omega_s \cdot k_s \tag{2.64}$$

$$R^{EE} = \sum_s P_s^E \cdot \omega_s \cdot o_s \tag{2.65}$$

$$C^A = \left[\frac{\phi \cdot (1+\phi)^t}{(1+\phi)^t - 1}\right] \cdot \left[\sum_m C_m \cdot r_m + \sum_n W_n \cdot b_n\right] \tag{2.66}$$

$$C^{FP} = \sum_s P_s^F \cdot \omega_s \cdot f_s \tag{2.67}$$

$$C^O = C^{FE} \cdot \sum_s \omega_s \cdot (e_s + o_s) + C^B \cdot \sum_s \omega_s \cdot D_s \tag{2.68}$$

$$C^{TF} = C^{FTF} \cdot \sum_s \omega_s \cdot f_s + \tau \cdot \overline{d} \cdot \sum_s C_s^{VTF} \cdot \omega_s \cdot f_s^E \tag{2.69}$$

$$C^{TE} = C^{FTE} \cdot \sum_s \omega_s \cdot e_s + \tau \cdot \overline{d} \cdot \sum_s C_s^{VTE} \cdot \omega_s \cdot e_s^E \tag{2.70}$$

$$C^{TEG} = C^{FTEG} \cdot \sum_s \omega_s \cdot D_s + \tau \cdot \overline{d} \cdot \sum_s C_s^{VTEG} \cdot \omega_s \cdot x_s^E \tag{2.71}$$

$$C^I = \sum_s P_s^{EI} \cdot \omega_s \cdot h_s + \sum_s P_s^{EE} \cdot \omega_s \cdot k_s \tag{2.72}$$

$$C^G = \sum_s P_s^G \cdot \omega_s \cdot [D_s - (e_s + h_s + k_s)] \tag{2.73}$$

$$J^C = \sum_s J_s^{Co} \cdot \omega_s \cdot \left[\sum_m C_m \cdot r_m + \sum_n W_n \cdot b_n\right] \tag{2.74}$$

$$J^{TF} = Q \cdot \tau \cdot \overline{d} \cdot \left[\sum_s J_s \cdot \omega_s \cdot f_s^E\right] \tag{2.75}$$

$$J^{TE} = Q \cdot \tau \cdot \bar{d} \cdot \left[\sum_s J_s^{TE} \cdot \omega_s \cdot e_s^E \right] \tag{2.76}$$

$$J^{TEG} = Q \cdot \tau \cdot \bar{d} \cdot \left[\sum_s J_s^{TEG} \cdot \omega_s \cdot x_s^E \right] \tag{2.77}$$

$$J^O = Q \cdot \sum_s J_s^{FE} \cdot \omega_s \cdot \left[\sum_m C_m \cdot r_m \right] + Q \cdot \sum_s J_s^B \cdot \omega_s \cdot \left[\sum_n W_n \cdot b_n \right] \tag{2.78}$$

where the distance approximation $\bar{d}$ in equations (2.69)-(2.71) and (2.75)-(2.77) equals either $\delta = \min_{i \neq j} d_{ij} > 0$ or $\Delta = \max_{i \neq j} d_{ij} > 0$. These will be used in the next section to explain the relationship between the GM and LM. The constraints (2.46-2.58) ensure that only external flows of corn stover, f_s^E, ethanol, e_s^E, and fuel, x_s^E, incur positive transportation costs, whereas the internal flows f_s^I, e_s^I, and x_s^I of corn stover, ethanol, and fuel respectively incur no such costs.

Therefore, the expected profit objective function and expected jobs created objective function are as follows:

$$L_1 = (R^R + R^S + R^{TL} + R^{TC} + R^{EE}) - (C^A + C^{FP} + C^O + C^{TF} + C^{TE} + C^{TEG} + C^I + C^G) \tag{2.79}$$

$$L_2 = J^C + J^{TF} + J^{TE} + J^{TEG} + J^O \tag{2.80}$$

respectively.

Observe that by (2.80) the objective L_2 does not depend on the Renewable Fuel Standard 2 (RFS2), the Blend Wall (BW), the Tax Credit for the US produced ethanol (TCL), the Tax Credit for the foreign produced ethanol (TCI), the Tariff for the US produced ethanol (TL), or the Tariff for the foreign produced ethanol (TI). Thus the changes in the government policies affecting these do not affect the maximization of L_2. Also, the L_2 is in conflict with the L_1 since the increase in the flows weighted by the distances, which may be a result of changes in bio-refineries or blending site locations, reduces L_1, the expected profit, while at the same time it increases L_2, the expected number of jobs created.

2.3.3 Relationship Between GM and LM

We have approximated the distance from one county to another county, d_{ij}, with $\overline{d}$ to make the GM completely converted to the aggregated model which is independent to counties, since without that C^{TF}, C^{TE}, and C^{TEG} in G_1, and J^{TF}, J^{TE}, and J^{TEG} in G_2 of the GM prevent full aggregation. Furthermore, to have a better bound we have used f_s^E, e_s^E, and x_s^E in these equations. To find the best value for $\overline{d}$, we used the following relations which exist between the GM and the LM in each scenario $s \in S$. Their proofs are given in Appendix 5.5.3:

Observation 1 *(Aggregation). Each feasible solution*

$$Y = (r_{mi}, b_{nj}, f_{jis}, e_{ijs}, o_{is}, h_{js}, k_{js}, g_{js}, x_{jis})$$

for the GM, can be converted into a feasible solution

$$X = (r_m, b_n, f_s, f_s^I, f_s^E, e_s, e_s^I, e_s^E, o_s, h_s, k_s, g_s, x_s, x_s^I, x_s^E)$$

for the LM using the equations in Appendix 2.5.2.

Observation 2 *(Disaggregation). Each optimal solution*

$$X = (r_m, b_n, f_s, f_s^I, f_s^E, e_s, e_s^I, e_s^E, o_s, h_s, k_s, x_s, x_s^I, x_s^E)$$

for the LM, can be converted into a feasible solution

$$Y = (r_{mi}, b_{nj}, f_{jis}, e_{ijs}, o_{is}, h_{js}, k_{js}, g_{js}, x_{jis})$$

for the GM. The conversion is not unique.

Observation 3 *For any α, β, η and θ, let X_{min} and X_{max} be optimal solutions to the LM with $\overline{d} = \delta$ and $\overline{d} = \Delta$ respectively, then $L_1(X_{\min}) \geq G_1(Y) \geq L_1(X_{\max})$ for an optimal solution Y to G_1 of the GM.*

Observation 4 *For any α, β, η and θ, let Z_{min} and Z_{max} be optimal solutions to the LM with $\overline{d} = \delta$ and $\overline{d} = \Delta$ respectively, then $L_2(Z_{\min}) \leq G_2(V) \leq L_2(Z_{\max})$ for an optimal solution V to G_2 of the GM.*

Finally, let us define L_1^{δ} and L_1^{Δ} to be the LM model with the objective L_1 where $\bar{d}$ is set to δ and Δ respectively. Similarly, let us define L_2^{δ} and L_2^{Δ} to be the LM model with the objective L_2 where $\bar{d}$ is set to δ and Δ respectively. We have the following observation:

Observation 5 *For any α, β, η and θ, let Y_{min} and Y_{max} be optimal solutions to the LM with the objective $L_1^{\Delta} + L_2^{\delta}$ and $L_1^{\delta} + L_2^{\Delta}$ respectively, then $L_1^{\Delta}(Y_{\min}) + L_2^{\delta}(Y_{\min}) \leq G_1(Y) \leq L_1^{\delta}(Y_{\max}) + L_2^{\Delta}(Y_{\max})$ for an optimal solution Y to $G_1 + G_2$ of the GM.*

2.4 Conclusions and Further Research

We studied the impact of Renewable Fuel Standard 2 (RFS2), Tax Credit (TCL and TCI), Tariff (TL and TI), and the Blend Wall (BW) on the SPSC. We proposed the General Model (GM) for the creation of the SPSC, which falls in the category of Multi-echelon Location-Allocation (LA) problems with uncertainty. The LA problem, even deterministic and a single-echelon, is NP-hard in the strong sense, thus computationally intractable. Therefore, the GM along with all other models of a general nature proposed in the literature is NP-hard in the strong sense. Hence it may be very time consuming to find an optimum for the GM for a *single* problem instance. This computational complexity makes those general models impractical as models to study policy impacts where *thousands* of instances need to be solved to optimality in computational experiments in reasonable time. Thus, we proposed a Lean Model (LM) to study the impact. The leanness comes at the cost of losing some details about flows in the SPSC which, however, may be not that important at the initial stage of the SPSC. The concept of aggregation behind the LM as well as the model itself stand on their own and seem worthy of further research in the context of other optimization problems where general models are too time consuming to solve to optimality. We did a case study for the State of Nebraska, one of the main corn stover producers in the US, using the LM, please see the accompanying part II (Ghahremanlou and Kubiak 2020d), to provide insights for the decision makers and investors who are willing to invest in the SPSC in order to make profit, to fulfill the US government regulations, and at the same time to meet the demand for the fuel in the State. These insights help in arriving at robust decisions.

We would like to emphasize the need for optimization algorithms for the multi-echelon location-allocation problems, both deterministic and stochastic, capable of competing with the standard solvers like Gurobi for solving real-life instances with close to a hundred potential locations in reasonable time. The challenge has not yet been met which creates ample opportunities for research that could impact the SPSC research. The optimal solutions to the LM can be efficiently obtained by Gurobi, which is shown by our computational experiments. They provide lower and upper bounds for optimal solutions of the GM which can be viewed as a stochastic multi-echelon location-allocation problem. The bounds and their corresponding solutions may then be used to speed up optimization algorithms for the GM which is another promising path for further research. So are heuristics and metaheuristics for the GM; to our knowledge neither of them have been proposed for the GM or other general models in the literature.

The paper considers two-objectives yet it focuses on the expected annual profit as the primary objective and uses optimal solutions for that objective to evaluate the secondary objective which is the expected number of jobs created during the life-time of the project. Other approaches to dealing with multiple objectives include an objective which is a convex combination of the two or the construction and analysis of Pareto frontier. Either creates an interesting venue for research aimed at providing further insights into the expected profit - expected number of jobs created trade-off. However, one needs to keep in mind that those approaches are typically used for a single instance, not for thousands of them required to study the policy impact which may further increase complexity. All these provide many opportunities for further research on the SPSC.

We used stochastic programming optimization to study the impact of policy change on the SPSC in our computational experiments. Further research into the impact could be stimulated by new approaches like the stochastic hybrid system method, see Temoçin and Weber (2014) for instance. The method has recently been successfully used in numerical approximation of portfolio optimization (Savku et al. 2014). Moreover, our optimization was mainly based on annual expected profit objective. However, the objectives based on conditional value-at-risk have been extensively studied in the context of supply chain portfolio optimization by Sawik (2017), and in robust portfolio optimization by Kara et al. (2019) where robust optimization is applied to conditional value-at-risk optimization dealing with uncertain data. Finally, it is worth observing that stochastic programming optimization assumes a centralized SPSC, and relaxation of this assumption may stimulate research on supply chains that allow various locations to form coalitions in order to share costs. Cooperation like this can be modeled using facility location games under uncertainty, see Usta et al. (2019) for an application of cooperative interval game theory to a housing problem.

2.5 Appendix

2.5.1 Notations

	Sets
N	set of counties
S	set of scenarios
	Indices
i	county index, $i \in N$
j	county index, $j \in N$
m	capacity level of bio-refineries $m \in \{1,2,3\}$
n	capacity level of blending sites $n \in \{1,2,3,4,5,6\}$
s	scenario index, $s \in S$
	Decision variables
	Continuous non-negative variables for scenario $s \in S$
o_{js}	amount of ethanol sold to exporter from bio-refinery in county j (gal)
e_{ijs}	amount of ethanol shipped from bio-refinery in county i to blending site in county j (gal)
f_{jis}	amount of feedstock (corn stover) shipped from harvesting site in county j to bio-refinery in county i (MT)
g_{js}	amount of petroleum gasoline purchased for blending with ethanol in blending site in county j (gal)
h_{js}	amount of ethanol purchased from other states for blending with gasoline in blending site in county j (gal)

k_{js}	amount of ethanol purchased from other countries for blending with gasoline in blending site in county j (gal)
x_{jis}	amount of fuel (ethanol-gasoline blend) shipped from blending site in county j to distribution center in county i (gal)
	Binary variables
b_{nj}	equals 1 if a blending site with capacity level n is set up in county j
r_{mi}	equals 1 if a bio-refinery with capacity level m is set up in county i

Parameters

Harvesting sites

A_{js}	amount of feedstock (corn stover) at county j in scenario s (MT)
F	sustainability factor for harvesting site in each county
L	feedstock loss factor due to baling and loading in each county
	Bio-refineries and blending sites - design
B	amount of loan to set up bio-refineries and blending sites in the state under study (\$)
t	loan payback period (y)
ϕ	interest rate of the loan received for establishing bio-refineries and blending sites
C_m	cost to set up a bio-refinery with capacity level m
W_n	cost to set up a blending site with capacity level n (\$)
U_m	capacity of a bio-refinery with capacity level m (MT)
H_n	capacity of a blending site with capacity level n (gal)
Q	lifetime of the bio-refineries and blending sites (y)
	Bio-refineries and blending sites - operation
C^{FE}	conversion cost per unit of ethanol produced (\$/gal)

V	conversion factor for bio-refineries (corn stover to ethanol) (gal$/MT$)
C^B	blending cost per unit of ethanol-gasoline blend produced (\$/gal)
E	maximum amount of ethanol can be imported from other states (gal)
J_s^{Co}	number of jobs created per dollar of expenditures on construction of bio-refineries and blending sites in scenario s ($job/\$ \cdot$ y)
J_s^{FE}	number of jobs created annually per dollar of expenditures on conversion operation in scenario s ($job/\$ \cdot$ y)
J_s^B	number of jobs created annually per dollar of expenditures on blending operation in scenario s ($job/\$ \cdot$ y)

Unit prices

P_s^F	price of feedstock purchased in scenario s (\$$/MT$)
P_s^E	price of ethanol sold to the exporter in scenario s (\$/gal)
P_s^{EI}	price of ethanol purchased from other states in scenario s (\$/gal)
P_s^{EE}	price of ethanol purchased from other countries in scenario s (\$/gal)
P_s^G	price of gasoline (from crude oil) purchased in scenario s (\$/gal)
P_s	price of fuel (ethanol-gasoline blend) sold to the distribution centers in scenario s (\$/gal)
P^R	price of RIN (\$$/RIN$)

Distribution centers

D_{is}	fuel (ethanol-gasoline blend) demand at county i in scenario s (gal)

Transportation

C^{FTF}	feedstock fixed transportation cost (\$$/MT$)
C_s^{VTF}	feedstock variable transportation cost in scenario s (\$$/MT \cdot$ mi)
C^{FTEG}	fuel (ethanol-gasoline blend) fixed transportation cost (\$/gal)

C_s^{VTEG}	fuel (ethanol-gasoline blend) variable transportation cost in scenario s ($\$/\text{gal}\cdot\text{mi}$)
C^{FTE}	ethanol fixed transportation cost ($\$/\text{gal}$)
C_s^{VTE}	ethanol variable transportation cost in scenario s ($\$/\text{gal}\cdot\text{mi}$)
d_{ij}	direct distance from county i to county j (mi)
J_s	number of jobs created for feedstock transported in scenario s ($job/MT\cdot\text{mi}\cdot\text{y}$)
J_s^{TEG}	number of jobs created for fuel transported in scenario s ($job/\text{gal}\cdot\text{mi}\cdot\text{y}$)
J_s^{TE}	number of jobs created for ethanol transported in scenario s ($job/\text{gal}\cdot\text{mi}\cdot\text{y}$)
τ	tortuosity factor (for converting direct distance to real distance)

Policies

M_s	amount of ethanol mandate for the state under study in scenario s (gal)
$\overline{R}$	renewable fuel standard for first generation of ethanol
$\overline{\overline{R}}$	renewable fuel standard for second generation of ethanol
T	tax credit per unit of ethanol (locally produced and/or imported from other states) blended with petroleum gasoline ($\$/\text{gal}$)
$\overline{T}$	tax credit per unit of ethanol (imported from other countries) blended with gasoline (coming from crude oil) ($\$/\text{gal}$)
α	blend wall
β	coefficient of current ethanol mandate
η	coefficient of current tax credit for blended ethanol (that locally produced and/or imported from other states)
θ	coefficient of current tax credit for blended ethanol (that imported from other countries)
RIN_s	amount of RINs for scenario s

General

ω_s	probability of scenario s

Objective function components

Revenues ($)

R^R	total revenue resulting from RINs sold
R^S	total revenue resulting from fuel (ethanol-gasoline blend) sold
R^{TL}	total revenue resulting from tax credit for blended ethanol (locally produced)
R^{TC}	total revenue resulting from tax credit for blended ethanol (imported from other countries)
R^{EE}	total revenue resulting from ethanol sold to the exporter

Costs ($)

C^A	total cost resulting from the annual loan payback
C^{FP}	total cost resulting from feedstock purchased
C^O	total cost resulting from bio-refineries and blending sites operation (conversion and blending)
C^{TF}	total cost resulting from transportation of feedstock (corn stover)
C^{TE}	total cost resulting from transportation of ethanol from bio-refineries to blending sites
C^{TEG}	total cost resulting from transportation of fuel (ethanol-gasoline blend) from blending sites to distribution centers
C^I	total cost resulting from ethanol imported from other states and other countries
C^G	total cost resulting from gasoline (from crude oil) purchased

Jobs (job)

J^C	total jobs resulting from construction of bio-refineries and blending sites

J^{TF} total jobs resulting from transportation of feedstock (corn stover)

J^{TE} total jobs resulting from transportation of ethanol from bio-refineries to blending sites

J^{TEG} total jobs resulting from transportation of fuel (ethanol-gasoline blend) from blending sites to distribution centers

J^{O} total jobs resulting from bio-refineries and blending sites operation (conversion and blending)

2.5.2 Aggregated Variables

The variables of the Lean Model (LM) and the General Model (GM) are related by equations (2.81-2.95) listed below. The equations informally state that the value of a variable in the LM is obtained by an *aggregation* of the values of variables in the GM over all counties, or conversely the values of variables in the GM are obtained by a *disaggregation* of the value of the variable in the LM. The disaggregation is not unique.

$$\sum_i r_{mi} = r_m, \qquad \forall m \tag{2.81}$$

$$\sum_j b_{nj} = b_n, \qquad \forall n \tag{2.82}$$

$$\sum_j \sum_i x_{jis} = x_s, \qquad \forall s \in S \tag{2.83}$$

$$\sum_j \sum_{i=j} x_{jis} = x_s^I, \qquad \forall s \in S \tag{2.84}$$

$$\sum_j \sum_{i \neq j} x_{jis} = x_s^E, \qquad \forall s \in S \tag{2.85}$$

$$\sum_j h_{js} = h_s, \qquad \forall s \in S \tag{2.86}$$

$$\sum_j k_{js} = k_s, \qquad \forall s \in S \tag{2.87}$$

$$\sum_i \sum_j e_{ijs} = e_s, \qquad \forall s \in S \tag{2.88}$$

$$\sum_i \sum_{j=i} e_{ijs} = e_s^I, \qquad \forall s \in S \tag{2.89}$$

$$\sum_i \sum_{j \neq i} e_{ijs} = e_s^E, \qquad \forall s \in S \tag{2.90}$$

$$\sum_j g_{js} = g_s, \qquad \forall s \in S \tag{2.91}$$

$$\sum_j \sum_i f_{jis} = f_s, \qquad \forall s \in S \tag{2.92}$$

$$\sum_j \sum_{i=j} f_{jis} = f_s^I, \qquad \forall s \in S \tag{2.93}$$

$$\sum_j \sum_{i \neq j} f_{jis} = f_s^E, \qquad \forall s \in S \tag{2.94}$$

$$\sum_i o_{is} = o_s, \qquad \forall s \in S \tag{2.95}$$

The total demand in the state in scenario s.

$$\sum_i D_{is} = D_s, \qquad \forall s \in S \tag{2.96}$$

The total supply of corn stover in the state in scenario s.

$$\sum_j A_{js} = A_s, \qquad \forall s \in S \tag{2.97}$$

2.5.3 Proofs of Relationship Between GM and LM

Proof. *Observation 1* – We set $P^i_{mn} = 1$ if and only if $r_{mi} = 1$ and $b_{in} = 1$ for all m, n, and $i \in N$. Thus $P^i_{mn} = 1$ if and only if a bio-refinery of size U_m and a blending site of size H_n are both set up in county i. By (2.1), (2.2), and (2.3) which are satisfied by Y, and using definitions (2.81) and (2.82) (see Appendix 2.5.2) we have (2.34), (2.35), (2.36), (2.46), (2.47), (2.49), (2.50), (2.57), and (2.58) satisfied by X. By definitions (2.88), (2.92), (2.95), and (2.97), the flow constraints (2.4), (2.5), and (2.6) met by Y imply that X meets (2.37), (2.38), and (2.39). Definitions (2.92), (2.93), and (2.94) imply (2.43) for the corn stover flow in X, (2.88), (2.89), and (2.90) imply (2.44) for the ethanol flow in X, and definitions (2.83), (2.84), and (2.85) along with the constraints (2.46) and (2.47) met for Y imply (2.45) for the fuel flow in X. The constraints (2.7), (2.8), (2.9), (2.10), and (2.11) satisfied by X by definitions (2.88), (2.86), (2.91), (2.87), (2.95), and (2.96) imply that the constraints (2.40), (2.41), and (2.42) are satisfied by X.

The maximum amount of feedstock shipped internally within county i with a bio-refinery of size U_m equals $B^m_{js} = \min\{A_{js} \cdot (1-F) \cdot (1-L), U_m\}$ for $m = 1,2,3,\ j = 1,\ldots,|N|$, and $s \in S$, thus the actual amount, f^I_s, shipped in Y meets the constraint (2.48) in X by definition (2.93). The maximum amount of fuel shipped internally within county i with a blending site of size H_n equals $C^n_{js} = \min\{D_{js}, H_n\}$ for $n = 1,\ldots,6,\ j = 1,\ldots,|N|$, and $s \in S$. Therefore, the actual amount, x_s^I, shipped in Y meets the constraint (2.51) in X by definition (2.84). Finally, the maximum amount of ethanol shipped internally within county i with a bio-refinery of size U_m and a blending site of size H_n equals $E_{mn} = \min\{V \cdot U_m, \alpha \cdot H_n\}$ for $m = 1,2,3$, and $n = 1,...,6$, thus the actual amount, e_s^I, shipped in Y meets the constraint (2.56) in X by definition (2.89). ■

Proof. *Observation 2* – Let $X = (r_m, b_n, f_s, f_s^I, f_s^E, e_s, e_s^I, e_s^E, o_s, h_s, k_s, x_s, x_s^I, x_s^E)$ be an optimal solution to the LM. We obtain a feasible solution to the GM as follows. First, locate a bio-refinery of size U_m in county j if and only if $r_{mj} = 1$ in X, and locate a blending site of size H_n in county j if and only if $b_{nj} = 1$ in X. The constraints (2.46), (2.47), (2.49), and (2.50) of the LM guarantee that these locations satisfy the constraints (2.2) and (2.3) of the GM. Since X satisfies the budget constraint (2.34) so does Y satisfy (2.1) in the GM. Let *Bio* and *Bl* be the sets of counties with bio-refineries and blending sites respectively in Y. Consider the flow of corn stover. By (2.48) we get

$$\sum_{i \in Bio} \min\{A_{is} \cdot (1-F) \cdot (1-L), U^i\} \geq f_s^I, \tag{2.98}$$

which guarantees that the locations in *Bio* ensure the internal flow f_s^I required by X, here U^i is the capacity of the bio-refinery located in i. Thus, we can obtain an internal flow f_{iis} for each county i so that the total internal flow equals $f_s^I = \sum_i f_{iis}$ in scenario s. Once the internal flows of corn stover have been fixed we can calculate the external flow f_{ijs} of corn stover from county i to county j, $i \neq j$, to meet the total external flow f_s^E required by X. The flows f_{ijs} can be calculated by solving a minimum cost network flow problem N_f with a given flow f_s^E to minimize the corn stover variable transportation costs. The network node capacities (supply of feedstock in county i and capacity of bio-refinery in county i) are determined by the constraints (2.4) and (2.5) and further adjusted by the internal flows f_{iis} which are fixed before the external flows f_{ijs} for different i and j are calculate. The constraints (2.37), (2.38), and (2.43) guarantee that the flows f_{ijs} are feasible for Y. The feedstock flows also determine the amount of ethanol $V \cdot f_{js}$ produced in county j which will subsequently serve as the upper limit on the amount of ethanol e_{js} (produced in county j and used in the state) in the network flow problem N_e used to calculate ethanol flows consistent with the corn stover flows f_{ijs} in order to satisfy (2.6) in Y by (2.39) in X.

Now consider the flow of fuel. By (2.51) we get

$$\sum_{i \in Bl} \min\{D_{is}, H^i\} \geq x_s^I, \tag{2.99}$$

which guarantees that the locations in Bl ensure the internal flow x_s^I required by X, here H^i is the capacity of the blending site located in i. Thus, we can obtain an internal flow x_{iis} for each county i so that the total internal flow equals $x_s^I = \sum_i x_{iis}$ in scenario s. Once the internal flows have been fixed we can calculate the external flow x_{ijs} of fuel from county i to county j, $i \neq j$, to meet the total external flow x_s^E required by X. The flows x_{ijs} can be calculated by solving a minimum cost network flow problem N_x with a given flow x_s^E to minimize the fuel variable transportation costs. The network node capacities (fuel demand in county i) are determined by the constraint (2.11) and further adjusted by the internal flows x_{iis} which are fixed before the external flows x_{ijs} for different i and j are calculated. The constraint (2.45) guarantees that the flows x_{ijs} are feasible for Y. The fuel flows also determine the amount of fuel x_{js} produced in county j, which will subsequently serve as the upper limit on the amount of ethanol e_{is} in the network flow problem N_e used to calculate ethanol flows consistent with the fuel flows x_{ijs} in order to satisfy (2.10) in Y by (2.45) in X.

Finally, consider the flow of ethanol. Since X is optimal we have $P^j_{mn} = 1$ if and only if a bio-refinery of size U^m and a blending site of size H^n are both set up in county j. Thus, the internal flow of ethanol occurs only in counties having both a bio-refinery and a blending site set up, and (2.56) guarantees that those counties in $Bio \cap Bl$ ensure the amount e_s^I required by X. The remaining ethanol, e_s^E, is shipped from the counties $i \in Bio \setminus Bl$ to the counties $j \in Bl \setminus Bio$. The flow e_{ijs} can be calculated, once the internal flows e_{iis} have been fixed, by solving a minimum cost network flow problem N_e with a given flow e_s^E to minimize the ethanol variable transportation costs. The network node capacities are determined by the constraint (2.7), and the flows f_{js} and x_{js} that have already been calculated. They are further adjusted by the internal flows e_{iis}, which are fixed before the external flows e_{ijs} are calculated. The constraint (2.45) guarantees that the flows e_{ijs} are feasible for Y.

At this point we have shown how to obtain feasible corn stover flows f_{ijs}, ethanol flows e_{ijs}, and fuel flows x_{ijs} for the GM. Now, we can use equations $V \cdot f_{is} = e_{i,s} + o_{i,s}$ (see the constraint (2.6) in the GM), where $V \cdot f_{is} \leq V \cdot U^i$ and $\sum_i e_{is} = e_s$ and $\sum_i o_{is} = o_s$ to calculate the amount of ethanol o_{is} exported from county i in scenario s. Thus, we get (2.6) satisfied by Y since X satisfies (2.38) and (2.39). Moreover, we can use equations $e_{is} + h_{is} + k_{is} + g_{is} = D_{is}$ (see the constraint (2.10) in the GM), and inequalities $e_{is} + h_{is} + k_{is} + g_{is} \leq \sum_n H_n \cdot b_{ni}$ (see the constraint (2.7) in the GM), $e_{is} + h_{is} + k_{is} \leq \alpha \cdot (e_{is} + h_{is} + k_{is} + g_{is})$ (see the constraint (2.8) in the GM), and $\sum_i h_{is} \leq E$ (see the constraint (2.9) in the GM), $\sum_i h_{is} = h_s$, $\sum_i e_{is} = e_s$ and $\sum_i k_{is} = k_s$ to calculate the amount of ethanol h_{is} purchased from other states, or abroad, k_{is}, by county i, and the amount of gasoline, g_{is}, purchased by county i. Clearly, these amounts can be calculated, for instance, to minimize the cost of the purchases. Thus we get (2.7), (2.8), and (2.9) satisfied by Y since X satisfies (2.40), (2.41) and (2.42). Therefore, we get solution Y that is feasible for the GM. Clearly, the solution is not unique since the flows, for instance, can be calculated differently. ■

Proof. *Observation 3* – By Observation 1, Y can be converted into a feasible solution X to the LM. The only difference between $L_1(X)$ and $G_1(Y)$ consists in replacing the distances d_{ij} with a single distance δ, please check (2.69-2.71), (2.22-2.24), (2.75-2.77), and (2.29-

2.31). However we have

$$\delta \cdot f_s^E \leq \sum_j \sum_{i \neq j} f_{jis} \cdot d_{ji}, \qquad \forall s \in S,$$
$$\delta \cdot e_s^E \leq \sum_j \sum_{i \neq j} e_{ijs} \cdot d_{ij}, \qquad \forall s \in S,$$
$$\delta \cdot x_s^E \leq \sum_j \sum_{i \neq j} x_{jis} \cdot d_{ji}, \qquad \forall s \in S.$$

Therefore, $L_1(X) \geq G_1(Y)$. For an optimal solution X_{min} to the LM we have $L_1(X_{min}) \geq L_1(X)$, thus $L_1(X_{min}) \geq G_1(Y)$.

By Observation 2, X_{max} can be converted into a feasible solution Y' to the GM. The only difference between $L_1(X_{min})$ and $G_1(Y')$ consists in replacing the distances d_{ij} with a single distance Δ, please check (2.69-2.71), (2.22-2.24), (2.75-2.77), and (2.29-2.31). However, we have

$$\Delta \cdot f_s^E \geq \sum_j \sum_i f_{jis} \cdot d_{ji}, \qquad \forall s \in S,$$
$$\Delta \cdot e_s^E \geq \sum_j \sum_i e_{ijs} \cdot d_{ij}, \qquad \forall s \in S,$$
$$\Delta \cdot x_s^E \geq \sum_j \sum_i x_{jis} \cdot d_{ji}, \qquad \forall s \in S.$$

Therefore, $G_1(Y') \geq L_1(X_{max})$. For an optimal solution Y to the GM we have $G_1(Y) \geq G_1(Y')$, thus $G_1(Y) \geq L_1(X_{max})$. We proved that $L_1(X_{min}) \geq G_1(Y) \geq L_1(X_{max})$ as required.

■

Proof. *Observation 4* – The proof is similar to the proof of Observation 3 thus it will be omitted. ■

Proof. *Observation 5* – By Observation 1, Y can be converted into a feasible solution X to the LM. The only difference between $L_1^{\delta}(X) + L_2^{\Delta}(X)$ and $G_1(Y) + G_2(Y)$ consists in replacing the distances d_{ij} with a single distance δ in the objective L_1 and a single distance Δ in the objective L_2, please check (2.69-2.71), (2.22-2.24), (2.75-2.77), and (2.29-2.31). Therefore, $L_1^{\delta}(X) + L_2^{\Delta}(X) \geq G_1(Y) + G_2(Y)$. For an optimal solution Y_{min} we have $L_1^{\delta}(Y_{max}) + L_2^{\Delta}(Y_{max}) \geq L_1^{\delta}(X) + L_2^{\Delta}(X) \geq G_1(Y) + G_2(Y)$.

By Observation 2, Y_{min} can be converted into a feasible solution Y' to the GM. The only difference between $L_1^{\Delta}(X)+L_2^{\delta}(X)$ and $G_1(Y')+G_2(Y')$ consists in replacing the distances d_{ij} with a single distance Δ in the objective L_1 and a single distance δ in the objective L_2, please again check (2.69-2.71), (2.22-2.24), (2.75-2.77), and (2.29-2.31). Therefore, $L_1^{\Delta}(X)+L_2^{\delta}(X) \le G_1(Y')+G_2(Y')$. For an optimal solution Y we have $L_1^{\Delta}(Y_{min})+L_2^{\delta}(Y_{min}) \le G_1(Y')+G_2(Y') \le G_1(Y)+G_2(Y)$. ■

The following chapter is:

Ghahremanlou, D. and W. Kubiak (2020b). Impact of government policies on Sustainable Petroleum Supply Chain (SPSC): A case study - Part II (The State of Nebraska). *Decision Making in Manufacturing and Services*. **In Press**.

Chapter 3

Impact of government policies on Sustainable Petroleum Supply Chain (SPSC): A case study - Part II (The State of Nebraska)

Abstract The accompanying part I (Ghahremanlou and Kubiak 2020c) developed the Lean Model (LM), a two-stage stochastic programming model which incorporates Renewable Fuel Standard 2 (RFS2), Tax Credits, Tariffs, and Blend Wall (BW), to study policy impact on the Sustainable Petroleum Supply Chain (SPSC) using cellulosic ethanol. The model enables us to study the impact by running computational experiments more efficiently and consequently arriving at robust managerial insights much faster. In this paper, we present a case study of policy impact on the SPSC in the State of Nebraska using the model. The case study uses available real-life data. The study shows that increasing RFS2 does not impact the amount of ethanol blended with gasoline but it might lead to bankruptcy of the refineries. We recommend that the government consider increasing the BW because of its

positive economic, environmental and social impacts. For the same reason, we recommend that the tax credit for blending the US produced ethanol with gasoline be at least 0.189 $\frac{\$}{\text{gal}}$ and the tariff for imported ethanol be at least 1.501 $\frac{\$}{\text{gal}}$. These also make the State independent from foreign ethanol, thereby enhancing its energy security. Finally, change in policy impacts the SPSC itself, most importantly it influences strategic decisions, however setting up a bio-refinery at York county and a blending site at Douglas county emerge as the most robust location decisions against the policy change in the study.

3.1 Introduction

The US is the biggest corn exporter in the world (U.S. Department of Energy 2011; Gupta and Verma 2015). Central Illinois/Indiana, northern Iowa/southern Minnesota, and the areas along the Platte River in Nebraska are most suitable for corn stover collection in the US (Wilhelm et al. 2007). Nebraska is one of the states with the largest corn area planted. Moreover, the states of Iowa and Nebraska have largest ethanol nameplate capacity and operating production in the country (Renewable Fuels Association 2010). The state of Iowa has been studied from the SPSC and biofuel supply chain perspective, yet not the policy impact perspective, in literature, see Li et al. (2014), Li and Hu (2014), Li et al. (2015), Zhang and Hu (2013), Gebreslassie et al. (2012b), Shah (2013) and Kazemzadeh and Hu (2015). Therefore, we consider corn stover and the State of Nebraska as a feedstock and a geographical location respectively for the case study in this paper. To the best of our knowledge no study has focused exclusively on the state of Nebraska thus far.

This case study contributes by characterizing those policies (1) for which there is no ethanol production in Nebraska; (2) for which most environmentally friendly fuel is produced in Nebraska; (3) which make Nebraska an ethanol dependent state, relying on foreign ethanol for producing environmentally friendly fuel; by identifying (4) the most robust counties in which to set up bio-refineries and blending sites; (5) the most robust capacities for bio-refineries and blending sites. The case study also determines, for each policy, a range of (6) annual expected profit; (7) the expected number of jobs created in Nebraska over 30 years for solutions that maximize the annual expected profit. The study also identifies (8) policies that result in several benefits at the same time: most environmentally friendly fuel, highest expected number of jobs created, positive annual expected profit with minimum government budget expenditure, and the independence from foreign ethanol.

The rest of the paper is organized as follows: Section 3.2 summarizes the background information and provides the data employed in this study. Section 3.3 details the design of computational experiments. Section 3.4 analyzes the results of the computational experiments, and provides strategic and managerial insights and recommendations for the design of the SPSC. Section 3.5 summarizes policy recommendations, and provides conclusions and opportunities for further research. Appendix 3.6.1 and 3.6.2 provide data about annual corn stover and fuel demand in Nebraska.

3.2 Case Study

3.2.1 Distances Between Counties

We used ArcGIS 10.5 to find the direct distances between centers of the $N = 93$ counties of Nebraska.

3.2.2 Harvesting Site and Feedstock

The corn production in each county is reported by the United States Department of Agriculture in bushels (U.S. Department of Agriculture 2012). Each bushel (*bu*) of corn is equal to 21.5 kg dry corn, and the corn mass to corn stover mass ratio is estimated 1:1 (Graham et al. 2007). Therefore, accordingly we calculate the amount of the corn stover for each county, A_j, and report it in Table 3.8 in the Appendix.

3.2.3 Bio-refineries and Blending Sites

The base cost for establishing a bio-refinery (cellulosic ethanol) with base capacity $U_1 = 772,151.89 \frac{MT}{\text{y}}$ is $C_1 = 422.5\ M\$$, (Humbird et al. 2011). Furthermore, the base capacity and the base cost for a blending site are $H_1 = 36.59 \frac{M\text{gal}}{\text{y}}$ (Wight Hat Ltd. 2003b) and $W_1 = 2.6\ M\$$ respectively (U.S. Environmental Protection Agency 1980). We apply the following formula below to estimate the costs for bio-refineries and blending sites (Wright and Brown 2007):

$$\text{cost-level}_k = k^{0.6}\text{base cost}. \tag{3.1}$$

We considered three different capacity levels for bio-refineries. These are obtained by multiplying the base capacity by $k = 1$, 2, and 3 respectively. The multipliers are determined to provide a good fit with the distribution of feedstock for different scenarios. Consequently, the costs in million dollars ($M\$$) for the capacities $U_1 = 772,151.89$, $U_2 = 1,544,303.78$, and $U_3 = 2,316,455.67 \frac{MT}{\text{y}}$ (these were rounded for the computation) of bio-refineries are $C_1 = 422.5$, $C_2 = 640.39$, and $C_3 = 816.77$ respectively. Similarly, we calculate the costs for blending sites with six different capacity levels, by multiplying the base capacity by $k = 1$, 3, 5, 7, 9, 11 and denoting them by W_n for $n = 1,...,6$ respectively. The multipliers are determined to provide a good fit with the distribution of demand in different scenarios. Consequently, the costs in million dollars for the capacities $H_1 = 36.59$, $H_2 = 109.77$, $H_3 = 182.95$, $H_4 = 256.13$, $H_5 = 329.31$, and $H_6 = 402.49 \frac{M\text{gal}}{\text{y}}$ of blending sites are $W_1 = 2.6$, $W_2 = 5.03$, $W_3 = 6.83$, $W_4 = 8.36$, $W_5 = 9.72$, and $W_6 = 10.96$ respectively.

The cap on loan to establish bio-refineries and blending sites is assumed $B = 5.25$ $B\$$, with $\phi = 8\%$ interest rate, and $t = 30$ years return time. To calculate the cap, we considered 5 $B\$$ cap to establish bio-refineries as it was done in Kazemzadeh and Hu (2015) for Iowa with higher than Nebraska ethanol production; we then added 0.25 $B\$$ cap to establish blending sites (this amount is derived by finding a good fit with the distribution of demand for different scenarios).

According to Humbird et al. (2011), by investing $C_1 = 422.5$ $M\$$ to establish a bio-refinery of size U_1 one creates 60 jobs annually necessary to run that bio-refinery. Thus $J^{FE} = \frac{60}{422.5 \cdot 10^6}$. According to the U.S. Environmental Protection Agency (1980), by investing $W_1 = 2.6$ $M\$$ to establish a blending site of size H_1 one creates 24 jobs annually necessary to run that blending site. Thus $J^B = \frac{24}{2.6 \cdot 10^6}$. Furthermore, Kim and Dale (2015) shows 6.48 full time construction jobs per million dollars in the construction of a bio-refinery are created. Thus $J^{Co} = 6.48$.

Furthermore, the price of the fuel produced by blending sites is set to $P = \$1.96$, which is the average price of E85 and gasoline during 2016 (E85 Prices 2016). We found $E = 39.75 \cdot 10^6 \ \frac{\text{gal}}{\text{y}}$ by calculating the amount of corn stover available in the US (excluding Nebraska) and multiplying it by conversion factor V, see Table 3.1. Finally, there are three commercial cellulosic ethanol plants in the US, ABEGOA BIOENERGY, DuPont and POET-DSM, from which the cheapest price offered is by DuPont, $P^{EI} = \$3.45$ (Lux Research Inc. 2016).

3.2.4 Demand

We estimated the D_i fuel demand for each county of Nebraska, according to the formula below (U.S. Environmental Protection Agency 1980). The detailed data are in Table 3.9 in the Appendix.

$$D_i = (\frac{Population\ of\ county\ i}{Population\ of\ Nebraska}) \cdot Total\ gasoline\ consumption\ in\ Nebraska \tag{3.2}$$

3.2.5 Transportation

The cost for transportation of ethanol and fuel includes distance-fixed cost and distance-variable cost, $C^{FTE} = 0.02\ \frac{\$}{\text{gal}}$ and $C^{VTE} = 16.2 \cdot 10^{-5}\ \frac{\$}{\text{gal}\cdot\text{mi}}$ respectively (the variable cost=1.3 $\frac{\$}{\text{mi}\cdot truckload}$ and truck capacity= 8000 gal) (Chen and Fan 2012). Likewise, the cost for transportation of feedstock includes distance-fixed cost and distance-variable cost $C^{FTF} = 4.39\ \frac{\$}{MT}$ and $C^{VTF} = 0 \cdot 19\ \frac{\$}{MT\cdot\text{mi}}$, respectively (Searcy et al. 2007).The jobs created for the transportation of feedstock (corn stover) $J = 1.35 \cdot 10^{-6}\ \frac{job}{MT\cdot\text{mi}}$ (Kim and Dale 2015). The jobs created for transportation of ethanol and fuel are almost $J^{TE} = 3.98 \cdot 10^{-9}$ and $J^{TEG} = 3.72 \cdot 10^{-9}$ respectively; we calculated these numbers by converting J to the appropriate unit using their density (ethanol density= 6.5 $\frac{\text{lb}}{\text{gal}}$ (CAMEO Chemicals. 2010), 1 $MT := 2204.62$ lb (Wight Hat Ltd. 2003a), and fuel density= 6.073 $\frac{\text{lb}}{\text{gal}}$ (Wikimedia Foundation Inc. 2017)). The rest of the information about the parameters given in the problem is summarized in Table 3.1.

3.2.6 Scenario Generation

The uncertain parameters in this study are: feedstock availability (A_j), feedstock price (P^F), variable transportation cost (C^{VTF}, C^{VTE}, and C^{VTEG}), ethanol import prices (P^{EI} and P^{EE}), fuel price (P), gasoline price (P^G), ethanol exporting price (P^E), number of jobs created (J^{Co}, J, J^{TE}, J^{TEG}, J^{FE}, and J^B) and fuel demand (D_i). We group the uncertain parameters based on their correlations (Table 3.2) (Tong et al. 2013; Carneiro et al. 2010).

bio-refineries and blending sites - design		
Parameters	Amount (Unit)	References
B	$5.25 \cdot 10^9$ ($)	Assumption
t	30 (y)	Kazemzadeh and Hu (2015)
ϕ	8%	Humbird et al. (2011) and Kazemzadeh and Hu (2015)
Q	30 (y)	Humbird et al. (2011)
bio-refineries and blending sites - operation		
Parameters	Amount (Unit)	References
C^{FE}	0.864 ($/gal)	Humbird et al. (2011)
V	79 (gal/MT)	Humbird et al. (2011)
C^B	0.00327 ($/gal)	U.S. Environmental Protection Agency (1980)
E	$39.75 \cdot 10^6$ (gal/y)	U.S. Department of Agriculture (2012) and Humbird et al. (2011)
Unit prices		
Parameters	Amount (Unit)	References
P^F	60 ($/$MT$)	Klein-Marcuschamer et al. (2010)
P^E	2.15 ($/gal)	Humbird et al. (2011)
P^G	2.085 ($/gal)	AAA Gas Prices. (2017)
P^R	1.33 ($/$RIN$)	U.S. Environmental Protection Agency (2016)
P^{EE}	2.17 ($/gal)	Tsanova (2016)
Harvesting Sites		
Parameters	Amount (Unit)	References
F	72%	Kazemzadeh and Hu (2015)
L	5%	Tong et al. (2013)
Transportation		
Parameters	Amount (Unit)	References
C^{FTF}	4.39 ($/$MT$)	Searcy et al. (2007)
C^{VTF}	0.19 ($/$MT \cdot$ mi)	Searcy et al. (2007)
C^{FTEG}	0.02 ($/gal)	Chen and Fan (2012)
C^{VTEG}	$16.2 \cdot 10^{-5}$ ($/gal · mi)	Chen and Fan (2012)
C^{FTE}	0.02 ($/gal)	Chen and Fan (2012)
C^{VTE}	$16.2 \cdot 10^{-5}$ ($/gal · mi)	Chen and Fan (2012)
τ	1.29	Kazemzadeh and Hu (2015)
Policies		
Parameters	Amount (Unit)	References
$\overline{R}$	10.1%	U.S. Environmental Protection Agency (2017b)
$\overline{\overline{R}}$	0.128%	U.S. Environmental Protection Agency (2017b)
T	0.45 ($/gal)	Duffield et al. (2008)
$\overline{T}$	0.54 ($/gal)	Duffield et al. (2008)

Table 3.1: Parameters information

Group number	Group name	Uncertain Parameters
1	Feedstock Availability	1. Feedstock availability
2	Technology Evolution	1. Number of jobs created \$ spend on construction of bio-refineries and blending sites 2. Number of jobs created by conversion operation 3. Number of jobs created by blending operation 4. Number of jobs created $MT \cdot$ mi feedstock transported 5. Number of jobs created $jobs \cdot$ gal $\cdot$ mi fuel blend transported 6. Number of jobs created gal $\cdot$ mi of ethanol transported
3	Prices and Costs	1. Price of ethanol sold to the exporter 2. Price of ethanol purchased from other states 3. Price of ethanol purchased from other countries 4. Price of petroleum gasoline purchased 5. Price of fuel (ethanol-gasoline blend) sold 6. Feedstock price 7. Feedstock variable transportation cost 8. Fuel variable transportation cost 9. Ethanol variable transportation cost
4	Fuel Demand	1. Fuel demand

Table 3.2: Uncertain Parameters grouping

In the Technology Evolution group, the uncertain parameters are J^{Co}, J, J^{TE}, J^{TEG}, J^{FE}, and J^{B}. The research shows routine manual jobs and routine cognitive jobs have stagnated between 1980 and 2014. Martin Ford, a futurist, warns that in future most of the jobs will be broken and allocated to the machines to be done (The Economist. 2016). In the Prices and Costs category, the uncertain parameters are P^{F}, C^{VTF}, C^{VTE}, C^{VTEG}, P^{EI}, P^{EE}, P, P^{G}, and P^{E}. Gasoline and diesel (for transportation) are produced from crude oil, therefore their prices follow the same pattern (U.S. Energy Information Administration 2017b). Furthermore, Wisner (2009) shows prices of feedstock, gasoline and ethanol follow almost the same trend. Also, price of any ethanol-gasoline blend (fuel) follows the prices of gasoline and ethanol. Therefore, we conclude that all uncertain parameters in the category of Prices and Costs in Table 3.2 follow the same trend.

Each scenario $s \in S$ is a potential realization of an uncertain parameter. The scenarios are generated based on the average values of the parameters, historical data and estimation. For probability of each scenario we follow the study performed by Tong et al. (2013).

We consider three scenarios for A_j, namely, Base (25%), High (50%) and Low (25%), which means with probability 0.25 the A_j stays the same, with probability 0.5 the A_j increases, and with the probability 0.25 the A_j decreases. This convention is applied to all other scenarios generated. For the Base scenario, we take the corn stover production given in Table 3.8. In the High scenario we assume 28% increase in the production and in the Low scenario we assume 5% decrease in the production as compared to the Base scenario. The increase and decrease in the High and the Low scenarios respectively are the best and worst case corn production observed in the US from 2012 to 2017 (University of Nebraska. 2016). Likewise, for the Technology Evolution we also consider three scenarios: Base (25%), High (50%) and Low (25%). In the Base scenario we use the values we have already mentioned for the six uncertain parameters in the Technology Evolution group; for the High and the Low scenarios we assume 7% and 4% reduction respectively in those values due to automation and reduced dependency upon human resources. Regarding the prices and costs we have already mentioned, we consider two scenarios: High (50%) and Low (50%). In the High scenario the prices (1-6) and the costs (7-9) in this category increase by 10% and 1.5% respectively; while in the Low scenario the prices and the costs increase by 7% and 1% respectively (Tong et al. 2013). We consider two scenarios for fuel demand in counties of Nebraska: High (70%) and Low (30%). In the High scenario and Low scenario fuel demand increases 31% and decreases 15% respectively. These amounts are the maximum and minimum growth and decline of the fuel demand at Nebraska during 2006 to 2015, and their related probabilities are calculated based on the annual demand (Nebraska Department of Revenue 2017). All 36 possible scenarios and their probability (ω) distribution are given in Table 3.3.

It is worth pointing out that all the scenarios are generated for a single year, although the project life time is $Q = 30$ years. The reason being that the multi-period planning horizon, e.g., 30 years, in stochastic programming significantly increases the size of the scenario tree, Table 3.3. The exponential growth has been observed often (Huang 2005). In this paper we have 36 scenarios for 17 uncertain factors, see Table 3.2, thus for the 30 year planning horizon, there would be 36^{30} scenarios instead of 36. This would significantly increase the time complexity of the problem, which is already intractable for a single period.

3.3 Design of Computational Experiments

We run the tests to examine the impact of government policies on the SPSC. In particular we examine the effects of changing the following factors:

- Tax Credit for Local ethanol blended with gasoline ($TCL = \eta \cdot T$, $\forall \eta \geq 0$)
- Tax Credit for Imported ethanol from abroad blended with gasoline ($TCI = \theta \cdot \overline{T}$, $\forall \theta \geq 0$)
- Tariff for Local ethanol blended with gasoline ($TL = -\eta \cdot T$, $\forall \eta \leq 0$)
- Tariff for Imported ethanol from abroad blended with gasoline ($TI = -\theta \cdot \overline{T}$, $\forall \theta \leq 0$)
- RFS2 mandate for cellulosic ethanol ($\beta \cdot \overline{\overline{R}}$)
- Blend Wall (α).

The BW, α, is set to 10%, 15% or 85%. The cellulosic biofuel mandates specified in RFS2 for 2022 and 2016 (to improve the readability we use the abbreviations 22 and 16 instead of 2022 and 2016 respectively in the superscripts below) are $\overline{\overline{R}}^{22} \cdot g^{22} = 16$ and $\overline{\overline{R}}^{16} \cdot g^{16} = 4.25$ billion gallons respectively (U.S. Environmental Protection Agency 2017c), where g^{22} and g^{16} are gasoline consumptions for 2022 and 2016 respectively. Thus, we get

Feedstock availability	Technology evolution	Prices and Costs	Fuel demand	Scenarios	Probability
Base (25%)	Base (25%)	High (50%)	High (70%)	1	0.021875
			Low (30%)	2	0.009375
		Low (50%)	High (70%)	3	0.021875
			Low (30%)	4	0.009375
	High (50%)	High (50%)	High (70%)	5	0.04375
			Low (30%)	6	0.01875
		Low (50%)	High (70%)	7	0.04375
			Low (30%)	8	0.01875
	Low (25%)	High (50%)	High (70%)	9	0.021875
			Low (30%)	10	0.009375
		Low (50%)	High (70%)	11	0.021875
			Low (30%)	12	0.009375
High (50%)	Base (25%)	High (50%)	High (70%)	13	0.04375
			Low (30%)	14	0.01875
		Low (50%)	High (70%)	15	0.04375
			Low (30%)	16	0.01875
	High (50%)	High (50%)	High (70%)	17	0.0875
			Low (30%)	18	0.0375
		Low (50%)	High (70%)	19	0.0875
			Low (30%)	20	0.0375
	Low (25%)	High (50%)	High (70%)	21	0.04375
			Low (30%)	22	0.01875
		Low (50%)	High (70%)	23	0.04375
			Low (30%)	24	0.01875
Low (25%)	Base (25%)	High (50%)	High (70%)	25	0.021875
			Low (30%)	26	0.009375
		Low (50%)	High (70%)	27	0.021875
			Low (30%)	28	0.009375
	High (50%)	High (50%)	High (70%)	29	0.04375
			Low (30%)	30	0.01875
		Low (50%)	High (70%)	31	0.04375
			Low (30%)	32	0.01875
	Low (25%)	High (50%)	High (70%)	33	0.021875
			Low (30%)	34	0.009375
		Low (50%)	High (70%)	35	0.021875
			Low (30%)	36	0.009375

Table 3.3: Scenarios

$\overline{\overline{R}}^{22} = (\frac{16}{4.25} \cdot \frac{g^{16}}{g^{22}}) \cdot \overline{\overline{R}}^{16}$. We set $\overline{\overline{R}}^{16} = \overline{\overline{R}} = 0.128\%$, see Table 3.1. For an upper bound on $\overline{\overline{R}}^{22}$, we set $g^{22} = g^{16}$. Thus, $\beta \cdot \overline{\overline{R}} \leq \overline{\overline{R}}^{22}$, where $\beta \leq \frac{16}{4.25} \approx 3.76$. However, the government may possibly reduce the mandate to 0, thus $0 \leq \beta$. Therefore, we consider $0 \leq \beta \leq 3.76$, and discretize it by setting $\beta = 0.3 \cdot k$, when $k = 0, 1, ..., 12$, and by adding 3.76 to the discretized set. The reason for considering 0.3 as the coefficient for k is that β has increased 3.76 times over 7 years, which means an increase of 0.54 per year. RFS2 was ratified in 2007 planning for cellulosic mandate in 2016; this currently seems optimistic due to the lack of cellulosic ethanol production, which resulted in the government mandate waiver. Therefore, we have considered a 50% waiver for cellulosic ethanol, $\frac{0.54}{2} = 0.27$, which is rounded up to 0.3.

Tax Credit for one gallon of local ethanol blended with gasoline, TCL, is $T = \$0.45$, see Table 3.1. We assume the credit would not exceed the price $P^E = \$2.15$ of one gallon of ethanol produced locally in the US, otherwise the government would actually be paying for the ethanol produced locally and provide it free to the blenders. Thus, the Tax Credit T can only increase up to $\frac{P^E}{T} = \frac{2.15}{0.45} \approx 4.78$ times. Therefore, $0 \leq \eta \leq 4.78$. Similarly, we assume the Tariff for one gallon of local ethanol blended with gasoline, TL, would not exceed the price $P^E = \$2.15$, otherwise the local ethanol producers would be paying for the ethanol produced locally and provide it free to the blenders. Thus, the Tariff T can only increase up to $\frac{P^E}{T} = \frac{2.15}{0.45} \approx 4.78$ times, which gives $-4.78 \leq \eta \leq 0$. Since one equation would cover the Tax Credit and Tariff, we have $-4.78 \leq \eta \leq 4.78$. In a similar fashion, for the imported ethanol blended with gasoline, $\frac{P^E}{\overline{T}} = \frac{2.15}{0.54} \approx 3.98$. This results in $-3.98 \leq \theta \leq 3.98$. The intervals for η, $[-4.78, 4.78]$, and θ, $[-3.98, 3.98]$, are discretized as follows, $\eta = -4.77 + 0.4 \cdot k$, where $k = 0, 1, ..., 23$ and $\theta = -3.98 + 0.4 \cdot k$, where $k = 0, 1, ..., 19$ respectively. Finally, the values 4.78 and 3.98 are added to the discretized sets of η and θ respectively. To calculate a step for η and θ we look at the monetary difference between the Tax Credits $\overline{T} - T = 0.54 - 0.45 = 0.09$. The 0.09 $\frac{\$}{\text{gal}}$ is then considered as a value that the government might use as a step for the increase or decrease of $\overline{T}$ and T. Therefore, $\frac{\overline{T}-T}{T} = \frac{0.54-0.45}{0.45} = 0.2$ is dollar change relative to T, and $\frac{\overline{T}-T}{\overline{T}} = \frac{0.54-0.45}{0.54} \approx 0.17$ is dollar change relative to $\overline{T}$. Thus $\frac{0.2+0.17}{2} = 0.185$ is the average relative dollar change. Then, $\frac{0.185}{0.45} \approx 0.41$ is the average dollar change relative to T, and $\frac{0.185}{0.54} \approx 0.35$ is the average dollar change relative to $\overline{T}$. Therefore, we take $\theta = \eta = 0.4$ which is between 0.35 and 0.41, and which is the only multiple of 0.1 in that interval.

We ran the experiments to calculate $L_1(X_{\min})$ and $L_2(X_{\max})$, see Ghahremanlou and Kubiak (2020c) for definitions of $L_1, L_2, X_{\min}$, and $X_{\max}$, for all possible combinations of α, β, θ, and η. This results in $2 \cdot 3 \cdot 14 \cdot 25 \cdot 21 = 44,100$ different runs of the LM. The LM consists of 30,546 continuous variables, 2,520 binary variables, and 1,467 constraints. The model is coded in Python 2.7 (Python Software Foundation 2001), and it is solved to optimality using Gurobi 7.0 (Gurobi Optimizer LLC. 2008). The experiments were performed on a Dell computer with an Intel Core i5-2400 3.10 GHz CPU and 8 GB RAM.

3.4 Analysis of Results, and Recommendations

This section discusses the impact of the policy change on the SPSC. We report on the economic, environmental, and social impact in the following three subsections. The results presented in these subsections are derived by solving the LM with two objective functions: L_1 and L_2. Since the investment is required to create the SPSC, we consider the annual expected profit maximization objective function, L_1, as the primary objective, and solve the LM with L_1 to optimality. We approximate $\bar{d}$ in L_1 with $\delta = \min_{i \neq j} d_{ij} > 0$ and $\Delta = \max_{i \neq j} d_{ij} > 0$ (see Section 3.3 in Ghahremanlou and Kubiak (2020c)), to obtain two optimal solutions $X_{\min}$ and $X_{\max}$ respectively. The $X_{\min}$ and $X_{\max}$ are referred to as the best case and the worst case respectively since by Observation 3 in Ghahremanlou and Kubiak (2020c), $L_1(X_{\min}) \geq L_1(X_{\max})$ and investors prefer to have maximum expected profit,

$L_1(X_{\min})$, not the minimum expected profit, $L_1(X_{\max})$. To calculate the value of L_2, we plug $X_{\min}$ and $X_{\max}$ in L_2 to obtain the metrics $L_2(X_{\min})$ and $L_2(X_{\max})$. We have already observed that the *maximization* of L_2 by itself is not affected by the policy change for the RFS2 mandates, the Blend Wall, the Tax Credits, and the Tariffs. Therefore the maximization of L_2 by itself would make no sense in studying the impact. However, by choosing the solutions $X_{\min}$ and $X_{\max}$ to evaluate L_2 we make its value *sensitive* to the policy changes since both solutions are sensitive to those changes. This allows us to investigate the social aspect resulting from those solutions.

3.4.1 Economic Aspect

It is crucial to realize that without private investment, the government policy could not be easily carried out. Figures 3.1 and 3.2 show the maximum expected profit, L_1, for investors in the best case, $L_1(X_{\min})$, and the worst case, $L_1(X_{\max})$, respectively. The $L_1(X_{\min})$ and $L_1(X_{\max})$ are sensitive to α, β, θ, and η, which is explained in the following paragraphs. A side-by-side examination of plots (a) and (b), (c) and (d), (e) and (f) illustrates that for any α, θ, and η the expected profits $L_1(X_{\min})$ and $L_1(X_{\max})$ decrease when β, represented by the colorbar, increases (as the back views are colored yellow, which represents the highest values of β, and the front views are colored blue, which represents the lowest values of β). The comparison of the two figures for any α (e.g., plots (a) in Figures 3.1 and 3.2 for $\alpha = 10\%$) reveals that $L_1(X_{\min})$ and $L_1(X_{\max})$ follow the same pattern though $L_1(X_{\min}) \geq L_1(X_{\max})$ for any α, β, θ, and η, one should however observe that for any α, $L_1(X_{\min})$ and $L_1(X_{\max})$ are different, and that the transportation costs components, (69-71) in Ghahremanlou and Kubiak (2020c), of the objective function L_1 are indeed not redundant. To show the numerical differences between $L_1(X_{\min})$ and $L_1(X_{\max})$ for each $\alpha = 10\%, 15\%$ and 85%, we define the maximum difference $MaxD^{\alpha} = \max_i \{L_1(X_{\min}(\alpha,i)) - L_1(X_{\max}(\alpha,i))\}$, the minimum difference $MinD^{\alpha} = \min_i \{L_1(X_{\min}(\alpha, i)) - L_1(X_{\max}(\alpha, i))\}$, and the average difference

$$AD^{\alpha} = \frac{\sum_{i=1}^{i=7350} [L_1(X_{\min}(\alpha, i)) - L_1(X_{\max}(\alpha, i))]}{7350}, \tag{3.3}$$

where the $X_{\min}(\alpha, i)$ and $X_{\max}(\alpha, i)$ are the optimal solutions for the best and the worst case respectively with $\alpha = 10\%, 15\%$ and 85%, and with the i-th combination of β, θ, and η for $i = 1, 2, ..., 7350$; the 7350 in equation (3.3) is the number of combinations of β, θ, and η for any α, $14 \cdot 25 \cdot 21 = 7350$, see Section 3.3. We obtain the following in our experiments $MaxD^{10\%} = 190.32$, $MaxD^{15\%} = 226.37$ and $MaxD^{85\%} = 694.47$; $MinD^{10\%} = 102.11$, $MinD^{\alpha=15\%} = 102.11$, and $MinD^{\alpha=85\%} = 102.11$; $AD^{10\%} = 146.08$, $AD^{15\%} = 146.09$, and $AD^{85\%} = 397.23$. To show the influence of changing α on $L_1(X_{\min})$ and $L_1(X_{\max})$, plots (g) in Figures 3.1 and 3.2 are drawn. The three plots in red, blue and green are the three projections for $\alpha = 10\%$, 15% and 85% respectively of the expected profit L_1 for fixed β and θ and variable η. To better understand the difference between values of $L_1(X_{\min})$ for $\alpha = 10\%, 15\%$ and 85%, and the difference between values of $L_1(X_{\max})$ for $\alpha = 10\%, 15\%$ and 85%, for any β, θ and η, we compare them directly by defining

- $MaxP_1^{\alpha_1 \alpha_2} = \max_i \{L_1(X_{\max}(\alpha_2, i)) - L_1(X_{\max}(\alpha_1, i))\}$;
- $MaxP_2^{\alpha_1 \alpha_2} = \max_i \{L_1(X_{\min}(\alpha_2, i)) - L_1(X_{\min}(\alpha_1, i))\}$;
- $MinP_1^{\alpha_1 \alpha_2} = \min_i \{L_1(X_{\max}(\alpha_2, i)) - L_1(X_{\max}(\alpha_1, i))\}$;
- $MinP_2^{\alpha_1 \alpha_2} = \min_i \{L_1(X_{\min}(\alpha_2, i)) - L_1(X_{\min}(\alpha_1, i))\}$;

and accordingly deriving

- $MaxP_1^{10\%15\%} = 3835.520$, $MaxP_1^{15\%85\%} = 46244.449$ in the experiments;

- $MaxP_2^{10\%15\%} = 3871.566$, $MaxP_2^{15\%85\%} = 46712.547$ in the experiments;

- $MaxP_1^{10\%15\%} = 0$, $MaxP_1^{15\%85\%} = 0$ in the experiments;

- $MaxP_2^{10\%15\%} = 0$, $MaxP_2^{15\%85\%} = 0$ in the experiments.

We observe that $MinP_1^{\alpha_1\alpha_2} = MinP_2^{\alpha_1\alpha_2} = 0$, whenever there is no ethanol blended with gasoline, $B^{\alpha} = 0$, see Table 3.5. Thus the increase of α results in the increase of L_1 whenever there is ethanol blended with gasoline $B^{\alpha} \neq 0$, see Table 3.5; however, L_1 does not change if there is no ethanol blended with gasoline, $B^{\alpha} = 0$, see Table 3.5. Also, we observe that the increase in α reduces the relative increment in L_1: $\frac{MaxP_1^{10\%15\%}}{15-10} = 767.104$ and $\frac{MaxP_1^{15\%85\%}}{85-15} = 660.635$, or $\frac{MaxP_2^{10\%15\%}}{15-10} = 774.313$ and $\frac{MaxP_2^{15\%,85\%}}{85-15} = 667.322$. We actually observe that a stronger condition holds, namely, for any $i = 1,2,...,7350$, $P(10\%,15\%,i) \geq P(15\%,85\%,i)$, where $P(10\%,15\%,i) = \frac{L_1(X_{\max}(15\%,i)) - L_1(X_{\max}(10\%,i))}{15-10}$ and $P(15\%,85\%,i) = \frac{L_1(X_{\max}(85\%,i)) - L_1(X_{\max}(15\%,i))}{85-15}$. Similarly, $Q(10\%,15\%,i) \geq Q(15\%,85\%,i)$, for any $i = 1,2,...,7350$, where $Q(10\%,15\%,i) = \frac{L_1(X_{\min}(15\%,i)) - L_1(X_{\min}(10\%,i))}{15-10}$ and $Q(15\%,85\%,i) = \frac{L_1(X_{\min}(85\%,i)) - L_1(X_{\min}(15\%,i))}{85-15}$.

Moreover, when US ethanol is blended with gasoline, for any α, β, and θ with increasing $\eta \geq 0.02$, see Table 3.5, $L_1(X_{\min})$ and $L_1(X_{\max})$ will increase. Likewise, when foreign ethanol is blended with gasoline, for any α, β, and $\eta \leq -0.38$ with increasing $\theta \leq -2.38$, see Table 3.5, $L_1(X_{\min})$ and $L_1(X_{\max})$ will increase.

In order to simplify the presentation of data, we define *Minimum* $\eta(\alpha,\beta,\theta)$ to be the minimum η, if any, such that $L_1(X_{\min}) > 0$ (or $L_1(X_{\max}) > 0$) for given α, θ, and β. The investors expect their business profit to be always positive, i.e. find an optimal solution X, if any, such that $L_1(X) > 0$; on the other hand, the government attempts to utilize its budget, while meeting its goals. For instance, the government may not extend the Tax Credit for US ethanol (TCL), and foreign ethanol (TCI), by keeping θ and η unchanged, due to the allocation of funds, which might otherwise have been given to ethanol and gasoline

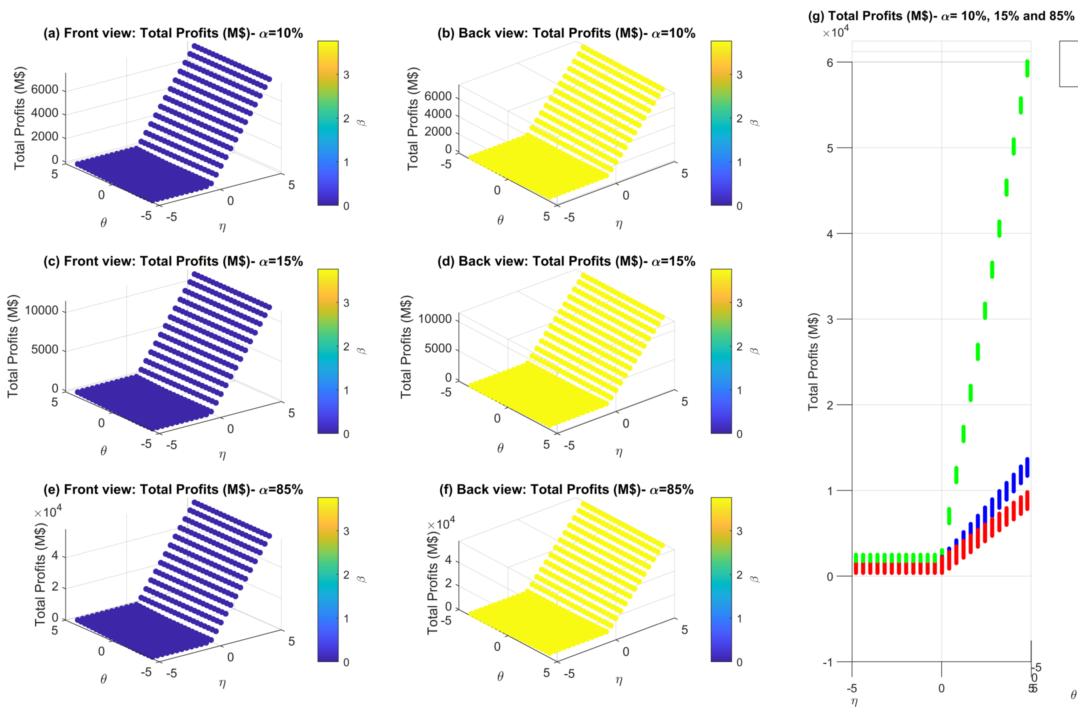


Figure 3.1: Expected profit for the best case, $L_1(X_{min})$, $\alpha = 10\%, 15\%$ and 85%

blenders as TCL and TCI from the budget, to other higher priority projects. Although, this might reduce the profitability of the investment, it should not lead it to a loss, $L_1 < 0$, or even worse, to a bankruptcy, as this would not help the government to meet its goals, for instance to create more environmentally friendly fuels. The *Minimum* $\eta(\alpha, \beta, \theta)$ is insensitive to β, so it is being omitted from Table 3.4. For $\alpha = 10\%$, for the best case and worst case, the *Minimum* $\eta(\alpha, \beta, \theta) = 0.42$ or -4.78. Similarly, for the best case and worst case, where $\alpha = 85\%$, the *Minimum* $\eta(\alpha, \beta, \theta) = 0.02$ or -4.78. While for the intermediate $\alpha = 15\%$ the *Minimum* $\eta(\alpha, \beta, \theta) = 0.42$ for the worst case (e.g., $\theta \in [-3.98, 3.22]$) is greater than the minimum 0.02 for the best case (e.g., $\theta \in [-3.98, 0.82]$). Generally, we observe that there are two minimum values of η to consider for each α, though they may be different for the worst and the best case. The switch from one to the other occurs once and the switch

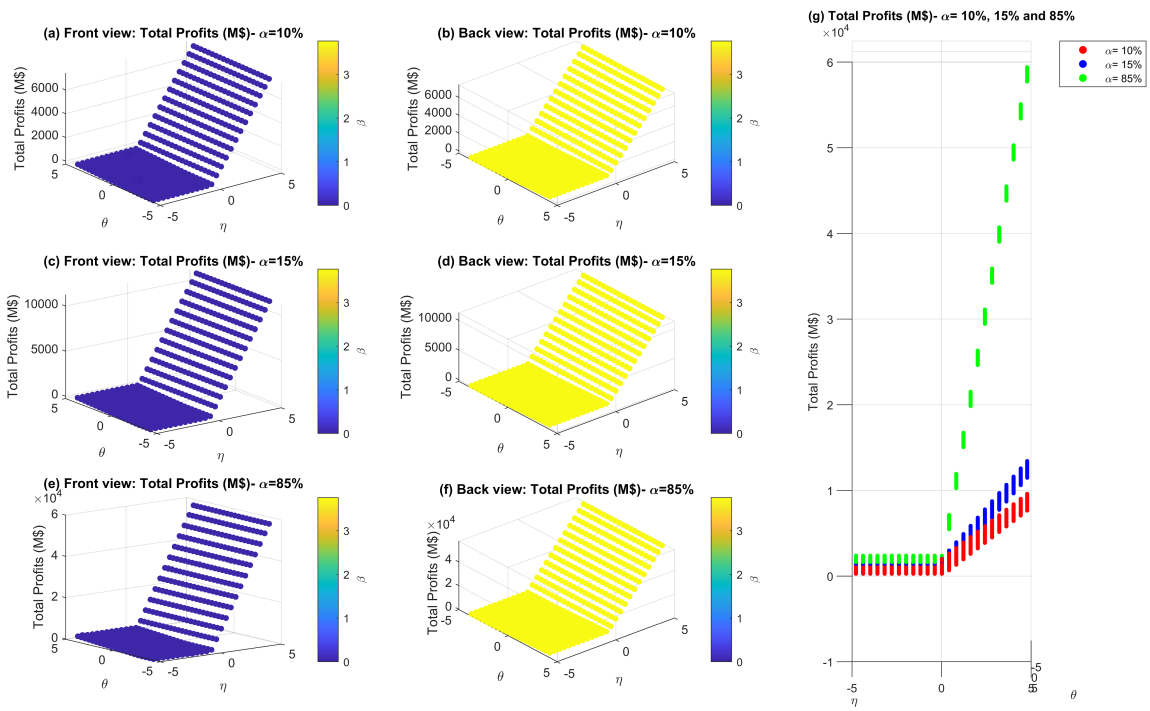


Figure 3.2: Expected profit for the worst case, $L_1(X_{max})$, $\alpha = 10\%, 15\%$ and 85%

requires higher θ for the worst case than for the best to occur.

	Minimum $\eta(\alpha,\beta,\theta)$	
α	The worst case	The best case
10%	$\begin{cases} 0.42 & if \quad \theta \in [-3.98, 3.22] \\ -4.78 & if \quad \theta \in [3.62, 3.98] \end{cases}$	$\begin{cases} 0.42 & if \quad \theta \in [-3.98, 0.82] \\ -4.78 & if \quad \theta \in [1.22, 3.98] \end{cases}$
15%	$\begin{cases} 0.42 & if \quad \theta \in [-3.98, 1.22] \\ -4.78 & if \quad \theta \in [1.62, 3.98] \end{cases}$	$\begin{cases} 0.02 & if \quad \theta \in [-3.98, -0.38] \\ -4.78 & if \quad \theta \in [0.02, 3.98] \end{cases}$
85%	$\begin{cases} 0.02 & if \quad \theta \in [-3.98, -1.98] \\ -4.78 & if \quad \theta \in [-1.58, 3.98] \end{cases}$	$\begin{cases} 0.02 & if \quad \theta \in [-3.98, -2.38] \\ -4.78 & if \quad \theta \in [-1.98, 3.98] \end{cases}$

Table 3.4: *Minimum* $\eta(\alpha,\beta,\theta)$ for the best case and the worst case, $\alpha = 10\%, 15\%$ and 85%

3.4.2 Environmental Aspect

A key reason to create the SPSC is the GHG emission reduction. The US, where gasoline is the main transportation fuel, is no exception. Clearly, blending more ethanol with gasoline is environmentally friendlier due to reducing the GHG. We define the average amount of ethanol blended with gasoline over 36 scenarios (see Table 3.3 for the definition of scenarios) for each experiment, i.e. the quadruple α, β, θ and η, as follows

$$B^{\alpha} = \left(\frac{\sum_{s=1}^{36} \frac{e_s + h_s + k_s}{D_s}}{36} \right) \cdot 100. \tag{3.4}$$

This value is calculated for the best case and the worst case in our experiments. Table 3.5 reports the average B^{α} over all experiments. The average is not sensitive to β, so this parameter is omitted from Table 3.5, however both θ and η impact the average. The best case and the worst case have the same average B^{α}, for each α, so they are omitted from the table. We observe that for $\alpha = 10\%$ and 15%, B^{α} follows the same pattern shown in the upper section of Table 3.5, where for $\alpha = 10\%$ and 15%, if $\eta \in [0.02, 4.78]$ or $\theta \in [-2.38, 3.98]$, the amount achieves the BW, $\alpha = 10\%$ or 15%. Otherwise, the average equals 0, which means that the policy results in no blending, and the SPSC is not created. For $\alpha = 85\%$ the pattern is different, there are two intermediate blends: $B^{85\%} = 76.81\%$ for $\theta \in [-3.98, -2.78]$ and $\eta = 0.02$, and $B^{85\%} = 77.12\%$ for $\theta \in [-3.98, -2.78]$ and $\eta \in [0.42, 4.78]$. Also, for any η and $\theta \in [-2.38, 3.98]$, $B^{85\%}$ reaches the BW, α.

3.4.3 Social Aspect

The creation of the SPSC, in response to the legislation, would generate jobs in construction, transportation, and operations. In particular it would aid in the development of rural

	$\alpha = 10\%$	η		
	$\alpha = 15\%$	$[-4.78, -0.38]$	$[0.02, 4.78]$	
θ	$[-3.98, -2.78]$	$B^{10\%} = B^{15\%} = 0\%$	$B^{10\%} = 10\%, B^{15\%} = 15\%$	
	$[-2.38, 3.98]$	$B^{10\%} = 10\%, B^{15\%} = 15\%$		
	$\alpha = 85\%$	η		
		$[-4.78, -0.38]$	0.02	$[0.42, 4.78]$
θ	$[-3.98, -2.78]$	$B^{85\%} = 0\%$	$B^{85\%} = 76.81\%$	$B^{85\%} = 77.12\%$
	$[-2.38, 3.98]$	$B^{85\%} = 85\%$		

Table 3.5: B^{α} for the best case and the worst case, $\alpha = 10\%, 15\%$ and 85%

areas, through the construction and operation of bio-refineries typically established closer to farms, the source of corn stover, in order to reduce its transportation cost. This is important because of corn stover low density. Tables 3.6 and 3.7 report the numbers of blending sites, b_n, and bio-refineries, r_m, established for each capacity, and the expected number of jobs created, L_2, in Nebraska during a 30 year time frame set for the SPSC. Recall that the L_2 does not depend directly on either α or β or θ, or η since neither of them occurs in the definition of L_2. The number of jobs created, L_2, is a secondary objective function in our experiments, thus $L_2(X_{\max})$ and $L_2(X_{\min})$ are calculated by plugging optimal solutions $X_{\max}$ and $X_{\min}$ to L_2 respectively. The $X_{\max}$ and $X_{\min}$ depend on α, β, θ, and η. Therefore the values $L_2(X_{\max})$ and $L_2(X_{\min})$ depend on the parameters α, β, θ, and η indirectly.

The highest positive social impact occurs for $\eta \in [0.42, 4.78]$, regardless of α, θ and transportation costs. Therefore, to have the highest positive social impact, while having the most environmentally friendly fuel ($B^{\alpha} = \alpha$, see Table 3.5), and having a positive expected profit with minimum incentive from the government, see Table 3.4, we recommend that the government considers $0.42 \cdot T = 0.42 \cdot 0.45 = 0.189 \frac{\$}{\text{gal}}$ tax credit for US ethanol (TCL), which gets blended with gasoline, regardless of other policy factors.

		The worst case		
	$\alpha = 10\%$	η		
	$\alpha = 15\%$	$[-4.78, -0.38]$	0.02	$[0.42, 4.78]$
θ	$[-3.98, -1.98]$	$r_1 = 0, b_1 = 45$ $b_6 = 0, L_2 = 40325$	$r_1 = 2, b_1 = 43$ $b_6 = 2, L_2^{10\%} = 65940$ $L_2^{15\%} = 74501$	
	-1.58		$r_1^{10\%} = 1, b_1^{10\%} = 44$ $b_6^{10\%} = 1, L_2^{10\%} = 59776$ $r_1^{15\%} = 2, b_1^{15\%} = 43$ $b_6^{15\%} = 2, L_2^{15\%} = 74501$	
	-1.18		$r_1 = 1, b_1 = 44$ $b_6 = 1, L_2 = 59776$	
	$[-0.78, 3.98]$			
$* \ r_2 = r_3 = b_4 = 0, b_2 = b_3 = b_5 = 1, \forall \eta, \theta$				
		The best case		
	$\alpha = 10\%$	η		
	$\alpha = 15\%$	$[-4.78, -0.38]$	0.02	$[0.42, 4.78]$
θ	$[-3.98, 0.42]$	$L_2 = 36949$	$L_2^{10\%} = 37101$ $L_2^{15\%} = 37178$	
	$[0.82, 3.98]$			
$* \ r_1 = r_2 = b_1 = b_3 = b_4 = b_5 = 0, r_3 = 3, b_2 = 1, b_6 = 2, \forall \eta, \theta$				

Table 3.6: Strategic decisions and number of jobs created for the worst case and the best case, $\alpha = 10\%$ and 15%

3.4.4 Further Strategic and Managerial Insights

We now, in Sections 3.4.4.1 and 3.4.4.2, compare the results of Tables 3.6 and 3.7 to identify the most robust decisions insensitive to policies and transportation costs. To summarize, if ($TI \geq 1.18 \cdot \overline{T} = 1.18 \cdot 0.54 = 0.637 \ \frac{\$}{\text{gal}}$ and $TCL = 0.02 \cdot T = 0.02 \cdot 0.45 = 0.009 \ \frac{\$}{\text{gal}}$) or ($TCL \geq 0.42 \cdot T = 0.42 \cdot 0.45 = 0.189 \ \frac{\$}{\text{gal}}$), we recommend that investors establish a bio-refinery at York county so that it could process the amount of corn stover from U_1 to U_3. Also, investors should set up a blending site at Douglas county so that it could deliver the amount of fuel from H_3 to H_6.

<table>
<tr><td colspan="2"></td><td colspan="3">The worst case</td></tr>
<tr><td></td><td>$\alpha = 85\%$</td><td colspan="3">η</td></tr>
<tr><td></td><td></td><td>$[-4.78, -0.38]$</td><td>0.02</td><td>$[0.42, 4.78]$</td></tr>
<tr><td rowspan="4">θ</td><td>$[-3.98, -2.38]$</td><td rowspan="4">$r_1 = 0, b_1 = 45$
$b_2 = 1, L_2 = 40325$</td><td>$r_1 = 11, b_1 = 35$
$b_2 = 12, L_2 = 202866$</td><td rowspan="4">$r_1 = 12, b_1 = 35$
$b_2 = 12, L_2 = 204742$</td></tr>
<tr><td>$[-1.98, -1.58]$</td><td>$r_1 = 9, b_1 = 36$
$b_2 = 10, L_2 = 188953$</td></tr>
<tr><td>-1.18</td><td>$r_1 = 7, b_1 = 38$
$b_2 = 8, L_2 = 160738$</td></tr>
<tr><td>$[-0.78, 3.98]$</td><td></td></tr>
<tr><td colspan="5">* $r_2 = r_3 = b_4 = b_6 = 0, b_3 = b_5 = 1, \forall \eta, \theta$</td></tr>
<tr><td colspan="2"></td><td colspan="3">The best case</td></tr>
<tr><td></td><td>$\alpha = 85\%$</td><td colspan="3">η</td></tr>
<tr><td></td><td></td><td>$[-4.78, -0.38]$</td><td>0.02</td><td>$[0.42, 4.78]$</td></tr>
<tr><td rowspan="3">θ</td><td>$[-3.98, -0.38]$</td><td rowspan="3">$r_2 = 0, r_3 = 3$
$b_2 = 1, b_3 = 0$
$b_4 = 0, b_6 = 2$
$L_2 = 36949$</td><td>$r_2 = 1, r_3 = 3$
$b_2 = 0, b_3 = 1$
$b_4 = 3, b_6 = 0$
$L_2 = 45566$</td><td rowspan="3">$r_2 = 0, r_3 = 4$
$b_2 = 0, b_3 = 1$
$b_4 = 3, b_6 = 0$
$L_2 = 47453$</td></tr>
<tr><td>$[0.02, 0.42]$</td><td>$r_2 = 0, r_3 = 3$
$b_2 = 0, b_3 = 1$
$b_4 = 3, b_6 = 0$
$L_2 = 38564$</td></tr>
<tr><td>$[0.82, 3.98]$</td><td></td></tr>
<tr><td colspan="5">* $r_1 = b_1 = b_5 = 0, \forall \eta, \theta$</td></tr>
</table>

Table 3.7: Strategic decisions and number of jobs created for the worst case and the best case, $\alpha = 85\%$

3.4.4.1 For $\alpha = 10\%$ and 15%

Table 3.6 displays b_n, r_m, and L_2 for $\alpha = 10\%$ and 15%. The b_n, r_m, and L_2 are insensitive to β, so it is omitted from the table. In the table, the b_n, r_m, and L_2 are almost same in the worst case for both $\alpha = 10\%$ and 15%. If they are not, they receive α as a superscript, which happens for ($TI \geq 1.18 \cdot \overline{T} = 1.18 \cdot 0.54 = 0.637 \frac{\$}{\text{gal}}$ and $TCL = 0.02 \cdot T = 0.02 \cdot 0.45 = 0.009 \frac{\$}{\text{gal}}$) or ($TCL \geq 0.42 \cdot T = 0.42 \cdot 0.45 = 0.189 \frac{\$}{\text{gal}}$), for instance, $r_1^{10\%} = 1$ and $r_1^{15\%} = 2$.

In the best case, the b_n, r_m, and L_2 are completely the same. The comparison of the best and the worst case provides the following key insights that hold regardless of the case:

- *Bio-refineries.* For ($TI \geq 1.18 \cdot \overline{T} = 1.18 \cdot 0.54 = 0.637 \ \frac{\$}{\text{gal}}$ and $TCL = 0.02 \cdot T = 0.02 \cdot 0.45 = 0.009 \ \frac{\$}{\text{gal}}$) or ($TCL \geq 0.42 \cdot T = 0.42 \cdot 0.45 = 0.189 \ \frac{\$}{\text{gal}}$), a bio-refinery should be established in York county. This location is robust against both the transportation cost change and policy change. A prudent approach is to set up the bio-refinery in this location so that it could process the amount of corn stover from U_1 to U_3.

- *Blending sites.* The most robust locations for establishing blending sites are Sarpy, Lancaster, and Douglas counties. These locations are robust against both the transportation cost change and policy change. The blending site located in Sarpy county should have capacity H_2. This is the most robust blending site since it does not need any capacity change either. However, the blending site in Douglas should be set up so it could deliver the amount of fuel from H_3 to H_6, and the blending site in Lancaster should be set up so that it could deliver the amount of fuel between H_5 and H_6.

- *Other insights.* There is a considerable difference between the b_n and r_m in the worst and the best cases. The former results in more than forty blending sites with total blending capacity more than $60 \cdot H_1$, whereas the latter results in only three blending sites with total capacity $25 \cdot H_1$. The $25 \cdot H_1$ blending capacity is sufficient to handle fuel demand which is the same for both cases; this clearly shows that in order to reduce high fuel transportation costs the SPSC needs to establish more blending sites. On the other hand, for $TI \geq 1.18 \cdot \overline{T} = 1.18 \cdot 0.54 = 0.637 \ \frac{\$}{\text{gal}}$ and ($TCL = 0.02 \cdot T = 0.02 \cdot 0.45 = 0.009 \ \frac{\$}{\text{gal}}$ or $TCL \geq 0.42 \cdot T = 0.42 \cdot 0.45 = 0.189 \ \frac{\$}{\text{gal}}$), the numbers of bio-refineries in the worst and best cases seem quite similar, though the capacity of bio-refineries is more than four times higher in the best case than in the worst. This shows that the higher feedstock transportation costs, the less ethanol is produced in the state since it may not be worth shipping more corn stover from farms to bio-refineries due to high transportation costs. Furthermore, since for $TI \geq 1.18 \cdot \overline{T} = 1.18 \cdot 0.54 = 0.637 \ \frac{\$}{\text{gal}}$ and ($TCL = 0.02 \cdot T = 0.02 \cdot 0.45 = 0.009 \ \frac{\$}{\text{gal}}$ or $TCL \geq 0.42 \cdot T = 0.42 \cdot 0.45 = 0.189 \ \frac{\$}{\text{gal}}$), the amount of ethanol blended with gasoline reaches the BW, $B^{\alpha} = \alpha$ in both the best and worst case, see Table 3.5, the extra amount of ethanol produced due to lower corn stover transportation costs will be sold to the exporters, see constraint (39) in Ghahremanlou and Kubiak (2020c). Finally, to obtain a positive expected profit, highest social impact, and the most environmentally friendly fuel, we recommend that the tax credit for blending US ethanol with gasoline be at least $TCL \geq 0.42 \cdot T = 0.42 \cdot 0.45 = 0.189 \ \frac{\$}{\text{gal}}$. Then only US ethanol is blended with gasoline which results in total ethanol independence.

3.4.4.2 For $\alpha = 85\%$

Table 3.7 displays b_n, r_m, and L_2 for $\alpha = 85\%$. The b_n, r_m, and L_2 are insensitive to β, so it is omitted from the table. The comparison of the best and the worst case provides the following key insights that hold regardless of the case:

- *Bio-refineries.* For $TI \geq 1.18 \cdot \overline{T} = 1.18 \cdot 0.54 = 0.637 \ \frac{\$}{\text{gal}}$ and ($TCL = 0.02 \cdot T = 0.02 \cdot 0.45 = 0.009 \ \frac{\$}{\text{gal}}$ or $TCL \geq 0.42 \cdot T = 0.42 \cdot 0.45 = 0.189 \ \frac{\$}{\text{gal}}$), three bio-refineries should be established in York, Custer, and Buffalo counties. These locations are robust against both the transportation cost change and policy change. A prudent approach is to set up the bio-refinery in each of these locations so that it could process the amount of corn stover from U_1 to U_3.

- *Blending sites.* The most robust locations for establishing a blending site is Douglas county. Again, this is insensitive to the transportation cost change and policy change.

The blending site located in Douglas county should be able to deliver the amount of fuel from H_4 to H_5.

- *Other insights.* Again there is a considerable difference between the b_n and r_m in the worst and best cases. The former results in more than forty blending sites with total blending capacity more than $50 \cdot H_1$, whereas the latter results in only three to four blending sites with total capacity of $25 \cdot H_1$ or $26 \cdot H_1$. The latter blending capacity is sufficient to meet fuel demand, which is the same for both cases. This clearly shows that in order to reduce high fuel transportation costs the SPSC needs to establish more blending sites, which remains consistent with the conclusion for $\alpha = 10\%$ and 15%. However, contrary to $\alpha = 10\%$ and 15%, for $TI \geq 1.18 \cdot \overline{T} = 1.18 \cdot 0.54 = 0.637\ \frac{\$}{\text{gal}}$ and ($TCL = 0.02 \cdot T = 0.02 \cdot 0.45 = 0.009\ \frac{\$}{\text{gal}}$ or $TCL \geq 0.42 \cdot T = 0.42 \cdot 0.45 = 0.189\ \frac{\$}{\text{gal}}$), the number of bio-refineries is approximately three times higher in the worst case than it is in the best case, which shows that in order to reduce high feedstock transportation costs the SPSC needs to establish more bio-refineries. Moreover, again contrary to $\alpha = 10\%$ and 15%, for $TI \geq 1.18 \cdot \overline{T} = 1.18 \cdot 0.54 = 0.637\ \frac{\$}{\text{gal}}$ and ($TCL = 0.02 \cdot T = 0.02 \cdot 0.45 = 0.009\ \frac{\$}{\text{gal}}$ or $TCL \geq 0.42 \cdot T = 0.42 \cdot 0.45 = 0.189\ \frac{\$}{\text{gal}}$), the capacity of bio-refineries remain almost similar for both the best and worst cases. This shows that contrary to $\alpha = 10\%$ and 15% the higher feedstock transportation costs do not reduce the amount of ethanol produced in the state since all the produced ethanol is blended with gasoline and nothing extra is produced to be sold to the exporters. Another important insight is that, for $\alpha = 10\%$ and 15%, if $TCL \geq 0.42 \cdot T = 0.42 \cdot 0.45 = 0.189\ \frac{\$}{\text{gal}}$ only the US ethanol is blended with gasoline for any θ. However for $\alpha = 85\%$, if $TCL \geq 0.42 \cdot T = 0.42 \cdot 0.45 = 0.189\ \frac{\$}{\text{gal}}$ this happens only if $TI \geq 2.78 \cdot \overline{T} = 2.78 \cdot 0.54 = 1.501$, otherwise if $TI \leq 2.38 \cdot \overline{T} = 2.38 \cdot 0.54 = 1.285\ \frac{\$}{\text{gal}}$ also foreign imported ethanol needs to be blended with gasoline. Hence for $\alpha =$

85% even the total corn stover available in the US may not be enough to meet the amount of ethanol required by Nebraska if $TCL \geq 0.42 \cdot T = 0.42 \cdot 0.45 = 0.189 \frac{\$}{\text{gal}}$ and $TI \leq 2.38 \cdot \overline{T} = 2.38 \cdot 0.54 = 1.285 \frac{\$}{\text{gal}}$, see constraints (38-41) in Ghahremanlou and Kubiak (2020c) and Appendix 3.2.3. Consequently, using the corn stover as the only source of cellulosic ethanol production in the US may lead to a drastic ethanol dependence for the US. To reduce this dependence, other feedstock and more efficient ethanol production technologies need to be required for cellulosic ethanol production to attain $\alpha = 85\%$. To achieve ethanol independence with the corn stover supply available in the US, a tariff of at least $TI \geq 2.78 \cdot \overline{T} = 2.78 \cdot 0.54 = 1.501 \frac{\$}{\text{gal}}$ for blending foreign ethanol with gasoline should be used. This would lead, however, to $B^{85\%} = 77.12\%$, which is below the BW, see Table 3.5. To obtain a positive expected profit, highest social impact, and the most environmentally friendly fuel ($B^{85\%} = 85\%$, see Table 3.5), we recommend that the tax credit for blending the US ethanol with gasoline to be at least $TCL \geq 0.42 \cdot T = 0.42 \cdot 0.45 = 0.189 \frac{\$}{\text{gal}}$, and the tariff for foreign ethanol to be blended with ethanol to be at most $TI \leq 2.38 \cdot \overline{T} = 2.38 \cdot 0.54 = 1.285 \frac{\$}{\text{gal}}$.

3.5 Conclusions and Further Research

We studied the impact of Renewable Fuel Standard 2 (RFS2), Tax Credit (TCL and TCI), Tariff (TL and TI), and the Blend Wall (BW) on the SPSC including only cellulosic ethanol. This study is performed based on the two-stage stochastic programming model developed by Ghahremanlou and Kubiak (2020c).

We conclude that if $TCL \geq 0.009 \frac{\$}{\text{gal}}$ or $TI \leq 1.285 \frac{\$}{\text{gal}}$, then ethanol is always blended with gasoline. Under these conditions an increase in the BW (α) for fixed β, η, and θ: (1) increases the expected annual profit of the SPSC, although, this increment is declining as α grows; (2) results in production of more environmentally friendly fuel; (3) keeps the expected number of jobs created steady or growing by keeping the numbers of bio-refineries and blending sites as well as their capacities steady or growing. Therefore, a strategy to increase the BW to 85% by, for instance, having only Flex-Fuel Vehicles registered, emerges as a rather promising direction for the US government to pursue. This strategy appears consistent with its recent decision to increase the BW to 15%, and with general observations of Vimmerstedt et al. (2012) based on system dynamics.

Assuming α, η, and θ are fixed, increasing RFS2, by increasing β: (1) reduces the expected profit by close to $P^R \cdot (1-\alpha) \cdot \beta \cdot \overline{\overline{R}} \cdot \sum_s D_s \cdot \omega_s$ whenever the blend gets close to the BW, α. This might result in bankruptcies if refineries are caught unprepared for the increase in RFS2; for instance, Philadelphia Energy Solutions, the largest U.S. East Coast oil refinery, blamed RFS2 for its bankruptcy (DiNapoli and Renshaw 2018; Simeone 2018; Stein 2018). Therefore, increasing RFS2 should be well planned and communicated in order to prevent the bankruptcies especially when the BW is low, e.g., $\alpha = 10\%$ and $TCL < 0.189$ $\frac{\$}{\text{gal}}$; (2) does not increase the amount of ethanol blended with gasoline, does not create new jobs, and does not affect the number of bio-refineries and blending sites, and their capacities.

If $TCL \geq 0.009$ $\frac{\$}{\text{gal}}$, then, assuming other policies are fixed, increasing TCL, the tax credit for the US produced ethanol, by increasing $\eta \geq 0$: (1) increases the expected annual profit; (2) provides incentives to produce the most environmentally friendly blend and to attain the highest number of jobs created under the policies by increasing the number of bio-refineries and blending sites, and their capacities. In contrast, increasing TL, the tariff for the US produced ethanol, by decreasing $\eta \leq 0$, does not affect either the expected annual profit, or the blend, or the number of new jobs created, since no US produced ethanol is then blended with gasoline. We observe that $TL = 0.38 \cdot 0.45 = 0.171$ $\frac{\$}{\text{gal}}$ or higher prevents blending US produced ethanol with gasoline. Therefore, if the government wants to replace cellulosic ethanol by other renewable transportation fuels, e.g., solar, it may consider $TL = 0.171$ $\frac{\$}{\text{gal}}$ or higher. We conclude that the TCL is crucial for the creation of the SPSC, which is consistent with the general observation of Vimmerstedt et al. (2012), and that the TL is only a good leverage to prevent blending US produced cellulosic ethanol with gasoline. Finally, if $TI \leq 1.285$ $\frac{\$}{\text{gal}}$, then, assuming other policies are fixed and $TCL \leq 0.009$ $\frac{\$}{\text{gal}}$, increasing TCI, the tax credit for foreign ethanol, by increasing $\theta \geq 0$: (1) increases the expected annual profit though the number of bio-refineries and blending sites as well as their capacities may be reduced as foreign produced cellulosic ethanol becomes more competitive than the US produced ethanol; (2) provides incentives to produce the most environmentally friendly blend; (3) does not create any new jobs in Nebraska. In contrast, increasing TI, the tariff for foreign imported ethanol blended with gasoline, by decreasing $\theta \leq 0$: (1) reduces the expected annual profit; (2) may reduce the environmental friendliness of the blend, since less ethanol is blended with gasoline; (3) may increase the number of jobs created, since there might be more bio-refineries set up in the State. To conclude, the government should be very careful while changing TCL, TL, TCI, and TI, since obtaining more environmentally friendly fuel may result in foreign ethanol dependency. To obtain a positive annual expected profit, higher social impact through new job creation, and more environmentally friendly blend, we recommend that the tax credit for blending the US produced ethanol be at least 0.189 $\frac{\$}{\text{gal}}$ ($TCL \geq 0.189$), and that the tariff on foreign produced ethanol not exceed 1.285 $\frac{\$}{\text{gal}}$ ($TI \leq 1.285$). However, by enacting these decisions the US would not be entirely ethanol independent from foreign ethanol. If the government wants also to achieve ethanol independence, it should consider $TI \geq 1.501$ $\frac{\$}{\text{gal}}$. This would lead to the most environmentally friendly blend. Moreover, $TCL \geq 0.189$ $\frac{\$}{\text{gal}}$ creates the most robust SPSC. Under this condition the investors should establish a bio-refinery at York county so that it could process the amount of corn stover from U_1 to U_3. Also, the investors should set up a blending site at Douglas county so that it could deliver the amount of fuel from H_3 to H_6.

For further research we recommend performing similar case studies for other countries with their own government policies impacting the SPSC, and their individual geography and feedstock. Also, running similar computational experiments for other states may result in new insights.

3.6 Appendix

3.6.1 Corn Stover in Nebraska

County	Corn Production (bu)	Corn Stover Production ($MT/$y)	County	Corn Production (bu)	Corn Stover Production ($MT/$y)
ADAMS	30,483,515	655,395.572	JEFFERSON	13,083,064	281,285.876
ANTELOPE	28,343,453	609,384.239	JOHNSON	3,717,106	79,917.779
ARTHUR	731,311	15,723.186	KEARNEY	26,745,156	575,020.854
BANNER	1,031,364	22,174.326	KEITH	14,069,787	302,500.420
BLAINE	356,582	7,666.513	KEYA PAHA	2,594,258	55,776.547
BOONE	22,377,218	481,110.187	KIMBALL	2,319,167	49,862.090
BOX BUTTE	8,759,886	188,337.549	KNOX	9,336,549	200,735.803
BOYD	1,087,708	23,385.722	LANCASTER	12,905,739	277,473.388
BROWN	4,345,453	93,427.239	LINCOLN	30,995,473	666,402.669
BUFFALO	34,718,498	746,447.707	LOGAN	3,081,790	66,258.485
BURT	14,992,221	322,332.751	LOUP	552,958	11,888.597
BUTLER	18,905,086	406,459.349	MADISON	14,399,309	309,585.143
CASS	12,047,078	259,012.177	MCPHERSON	330,660	7,109.19
CEDAR	17,307,388	372,108.842	MERRICK	17,971,471	386,386.626
CHASE	24,875,993	534,833.849	MORRILL	10,803,043	232,265.424
CHERRY	5,214,813	112,118.479	NANCE	7,384,287	158,762.170
CHEYENNE	4,953,382	106,497.713	NEMAHA	7,903,146	169,917.639
CLAY	25,411,112	546,338.908	NUCKOLLS	15,021,489	322,962.013
COLFAX	11,072,864	238,066.576	OTOE	11,131,722	239,332.023
CUMING	12,662,079	272,234.698	PAWNEE	4,128,138	88,754.967
CUSTER	35,567,025	764,691.037	PERKINS	22,673,105	487,471.757
DAKOTA	7,438,489	159,927.513	PHELPS	30,509,372	655,951.498
DAWES	864,463	18,585.954	PIERCE	15,904,085	341,937.827
DAWSON	32,718,282	703,443.063	PLATTE	24,904,119	535,438.558
DEUEL	2,554,325	54,917.987	POLK	17,395,817	374,010.065
DIXON	6,724,838	144,584.017	RED WILLOW	6,656,930	143,123.995
DODGE	19,969,493	429,344.099	RICHARDSON	10,041,640	215,895.26
DOUGLAS	4,265,616	91,710.744	ROCK	3,563,275	76,610.412
DUNDY	12,683,264	272,690.176	SALINE	19,136,024	411,424.516
FILLMORE	29,948,726	643,897.609	SARPY	4,278,624	91,990.416
FRANKLIN	11,674,498	251,001.707	SAUNDERS	21,099,076	453,630.134
FRONTIER	6,616,300	142,250.45	SCOTTS BLUFF	12,198,777	262,273.705
FURNAS	9,001,254	193,526.961	SEWARD	18,867,502	405,651.293
GAGE	15,033,856	323,227.904	SHERIDAN	4,927,216	105,935.144
GARDEN	3,291,520	70,767.68	SHERMAN	9,422,186	202,576.999
GARFIELD	2,140,111	46,012.386	SIOUX	2,323,374	49,952.541
GOSPER	12,896,553	277,275.889	STANTON	5,055,934	108,702.581
GRANT	0	0	THAYER	21,098,839	453,625.038
GREELEY	10,257,724	220,541.066	THOMAS	238,557	5,128.975
HALL	34,249,154	736,356.811	THURSTON	8,646,785	185,905.877
HAMILTON	34,678,560	745,589.04	VALLEY	10,207,594	219,463.271
HARLAN	13,247,036	284,811.274	WASHINGTON	8,949,375	192,411.562
HAYES	7,653,174	164,543.241	WAYNE	8,821,373	189,659.519
HITCHCOCK	2,915,946	62,692.839	WEBSTER	8,799,974	189,199.441
HOLT	33,211,151	714,039.746	WHEELER	4,444,482	95,556.363
HOOKER	0	0	YORK	37,406,032	804,229.688
HOWARD	13,186,780	283,515.77			

Table 3.8: Corn and Corn Stover production for each county in Nebraska (2012)

3.6.2 Population and Fuel Demand in Nebraska

County	Population	Fuel Consumption (Kgal/y)	County	Population	Fuel Consumption (Kgal/y)
ADAMS	31,684	11,318.45	JEFFERSON	7,177	2,563.83
ANTELOPE	6,329	2,260.90	JOHNSON	5,171	1,847.23
ARTHUR	469	167.54	KEARNEY	6,552	2,340.57
BANNER	798	285.07	KEITH	8,018	2,864.26
BLAINE	484	172.90	KEYA PAHA	791	282.57
BOONE	5,332	1,904.75	KIMBALL	3,679	1,314.25
BOX BUTTE	11,194	3,998.82	KNOX	8,571	3,061.81
BOYD	1,982	708.03	LANCASTER	309,637	110,611.38
BROWN	2,960	1,057.40	LINCOLN	35,550	12,699.50
BUFFALO	49,383	17,641.05	LOGAN	772	275.78
BURT	6,546	2,338.42	LOUP	591	211.12
BUTLER	8,052	2,876.41	MADISON	493	176.11
CASS	25,767	9,204.72	MCPHERSON	35,015	12,508.38
CEDAR	8,671	3,097.53	MERRICK	7,828	2,796.39
CHASE	3,937	1,406.41	MORRILL	4,787	1,710.06
CHERRY	5,832	2,083.36	NANCE	3,576	1,277.45
CHEYENNE	10,051	3,590.51	NEMAHA	6,971	2,490.24
CLAY	6,163	2,201.60	NUCKOLLS	4,265	1,523.58
COLFAX	10,414	3,720.18	OTOE	16,081	5,744.60
CUMING	9,016	3,220.78	PAWNEE	2,652	947.37
CUSTER	10,807	3,860.58	PERKINS	2,898	1,035.25
DAKOTA	20,465	7,310.70	PHELPS	9,266	3,310.09
DAWES	8,979	3,207.56	PIERCE	7,159	2,557.40
DAWSON	23,640	8,444.90	PLATTE	32,861	11,738.91
DEUEL	1,873	669.09	POLK	5,203	1,858.66
DIXON	5,762	2,058.35	RED WILLOW	10,722	3,830.21
DODGE	36,757	13,130.67	RICHARDSON	8,060	2,879.27
DOUGLAS	554,995	198,260.42	ROCK	1,390	496.55
DUNDY	1,831	654.09	SALINE	14,331	5119.45
FILLMORE	5,720	2,043.35	SARPY	179,023	63,952.24
FRANKLIN	3,014	1,076.69	SAUNDERS	21,038	7,515.39
FRONTIER	2,621	936.30	SCOTTS BLUFF	36,422	13,011.00
FURNAS	4,787	1,710.06	SEWARD	17,284	6,174.35
GAGE	21,799	7,787.24	SHERIDAN	5,234	1,869.74
GARDEN	1,930	689.45	SHERMAN	3,054	1,090.98
GARFIELD	2,011	718.39	SIOUX	1,242	443.68
GOSPER	1,971	704.10	STANTON	5,944	2,123.37
GRANT	641	228.98	THAYER	5,101	1,822.23
GREELEY	2,399	856.99	THOMAS	716	255.78
HALL	61,705	22,042.83	THURSTON	7,127	2,545.97
HAMILTON	9,186	3,281.51	VALLEY	4,184	1,494.65
HARLAN	3,473	1,240.66	WASHINGTON	20,603	7,359.99
HAYES	897	320.43	WAYNE	9,365	3,345.45
HITCHCOCK	2,825	1,009.17	WEBSTER	3,603	1,287.10
HOLT	10,250	3,661.60	WHEELER	776	277.21
HOOKER	708	252.92	YORK	13,794	4,927.62
HOWARD	6,429	2,296.63			

Table 3.9: Population and Fuel (ethanol-gasoline blend) consumption for each county in Nebraska (2016)

The following chapter is:

Ghahremanlou, D. and W. Kubiak (2020c). Sustainable Petroleum Supply Chains created during economic crisis in response to US government policies. *International Journal of Sustainable Economy*. **Submitted**.

Chapter 4

Sustainable Petroleum Supply Chains created during economic crisis in response to US government policies

Abstract Coronavirus Disease (COVID-19) and the Saudi Arabia-Russia Oil Price War have recently created economic catastrophe. This crippled the US Sustainable Petroleum Supply Chain (SPSC), which is created in response to government policies, as a solution to global warming and achieving energy independency. The government with policy leverages from one side, and the investors with supply chain management techniques from the other side, are striving to rescue the SPSC from bankruptcy, in particular refineries and biorefineries. This motivated us to investigate the requirements for creating a robust SPSC. In order to do this we extended the risk neutral study performed by Ghahremanlou and Kubiak (2020c) for regular economic conditions, in order to hedge the SPSC against financial risks. To that end, we propose a risk averse approach by applying Conditional Value-at-Risk (CVaR) and developing a two-stage stochastic programming model which incorporates government policies. To provide insights to the government about the best ways of

employing the policies to support the SPSC, we conduct a computational experiment with 22,050 policy scenarios for a case study at the county-level in Nebraska, and illustrate the advantages of employing CVaR in the given situation. Additionally, we provide to the investors some strategic investment decisions that can withstand economic crises. Our results show that during economic crises, for the survival of the SPSC, including only cellulosic bioethanol, government must at least consider 2.151 $\frac{\$}{\text{gal}}$ tax credit for US bioethanol blended with gasoline, and push the blend wall to at least 15%. We provide more insights for the government and investors in the Conclusion.
Keywords: Conditional Value-at-Risk, Sustainable Petroleum Supply Chain, Two-Stage Stochastic Programming, Government Policies

4.1 Introduction

Governments the world over ordered self isolation to prevent the spread of COVID-19, an airborne virus with a lengthy incubation period. This led to drastic reductions in national and international transportation. Additionally, the Saudi Arabia-Russia Oil Price War has hamstrung the demand for transportation fuel. The International Energy Agency (IEA) forecasts that by the end of May 2020 the demand for fuel will be reduced, globally, by close to 60% (Tagliapietra 2020). Plummeting fuel demand has imposed great financial pressure on the SPSC, specifically refineries and bio-refineries in the US, the biggest global oil and bioethanol producer. Whiting Petroleum Corp, the largest oil producer in North Dakota's Bakken region, has recently filled for bankruptcy (Nair 2020). Additionally, more than 1,100 bankruptcies are predicted given a \$10 per barrel oil price (Egan and CNN Business 2020). The low oil price has resulted in the closure of over 70 bio-refineries (Neeley 2020). Government is trying to intervene and rescue the SPSC (Drugmand 2020), which is created by merging the Bioethanol Supply Chain (BSC) with the Conventional

Petroleum Supply Chain (CPSC) (Tong et al. 2014). The SPSC evolved due to government policies to overcome global warming and energy insecurity (Sahebi et al. 2014b; Agarwal 2007; Yan 2012). Given the leading role of government policies and significance of the SPSC, it is quite important to figure out and analyze the optimal policy methods that government can utilize toward building a robust SPSC during such an economic crisis.

With the 1859 discovery of oil in the United States, the US Conventional Petroleum Supply Chain (CPSC) came to existence (Frehner 2011). Although the CPSC has encountered several crises throughout its history, e.g., oil crisis due to US embargo resulting from the 1973 Arab–Israeli War (Smith 2009) or the 2020 Saudi Arabia-Russia Oil Price War (Guliyev 2020), it has been a source of victory for the US; it helped the US and its allies to win both world wars and the Cold War (Painter 2012). Additionally, it fuels modern society; the U.S. Energy Information Administration (2019) announced that 92% of total US transportation fuel was derived from petroleum in 2018. The importance of the CPSC is also observed by many studies devoted to it, see Taqvi et al. (2019); Attia et al. (2019); Assis et al. (2019); Zhou et al. (2020); Yuan et al. (2020), for recent publications. However, global warming and energy security have led the US government to decide to substitute petroleum with renewable fuels derived from biological materials (Bamati and Raoofi 2020). Currently bioethanol derived from domestic resources is used as an additive to gasoline in most countries, including the US, due to market restrictions and infrastructure compatibility (Agarwal 2007; Yacobucci 2010; IHS Markit 2019).

Bioethanol Supply Chains (BSCs) are created to both reduce greenhouse-gas (GHG) emissions and make the countries energy independent (Tong et al. 2014; Ghahremanlou and Kubiak 2020c). The BSC developed due to government policies in the US in 1970s (Reitze 2001; Duffield et al. 2008; Dutton 1971) in response to two oil crises during this decade brought on by the 1973 Arab–Israeli War and the Iranian Revolution of 1979 (Smith 2009; Ilie 2006; Kesicki 2010). The crucial role of the BSC captured researchers' attention, see some of the recent publications in this area: Rahemi et al. (2020); Vikash and Shastri (2019); Akbarian-Saravi et al. (2020); Lan et al. (2020); Ahranjani et al. (2020); however, none has considered the government policies in their study, although the BSC is created by them.

The following US policies have created and merged the BSC with CPSC, which in turn formed Sustainable Petroleum Supply Chain (SPSC) (Kazemzadeh and Hu 2013; Ghahremanlou and Kubiak 2020c; Kazemzadeh and Hu 2015):

- Renewable Fuel Standard 2 (RFS2) – To guarantee a market for bioethanol, the RFS2 was included in the Energy Independence and Security Act (EISA), which was signed in 2007. According to RFS2, the gasoline refiners and gasoline importers in the US, called obligated parties, are supposed to blend a minimum amount of 1^{st}, 2^{nd} and 3^{rd} generation bioethanol (McPhail et al. 2011; Cornell Law School 2010), called mandate or Renewable Volume Obligation (RVO), with their gasoline each year to distribute in the market (Thompson et al. 2009; Duffield et al. 2008). The nested structure of RFS2 allows meeting the mandate for all generations of bioethanol by 2^{nd} generation bioethanol, as it is the most environmentally friendly bioethanol, with 60% GHG emission reduction, produced from cellulosic materials, e.g., corn stover; this is why it is also called cellulosic bioethanol (Baeyens et al. 2015; Thompson et al. 2009);

- Tax Credits – To encourage blending bioethanol with gasoline, the Volumetric Ethanol Excise Tax Credit (VEETC) was created in 2004. According to VEETC, blending each gallon of US and imported bioethanol with gasoline, TCL and TCI respectively, is entitled to $0.45 tax credit (McPhail et al. 2011). This might be good policy leverage for the time the oil prices decline and blending bioethanol with gasoline is not preferred, e.g. the Iranian Revolution of 1979 (Taxpayers for Common Sense 2020) or the 2020 Saudi Arabia-Russia Oil Price War;

- Tariffs – To support the US bioethanol industry and improve the energy independency 0.54 $\frac{\$}{\text{gal}}$ tariff for blending foreign bioethanol with gasoline, TI, was considered (McPhail et al. 2011). However, there may be occasions during which bio-refineries could be a lot more beneficial, for example, Voegele (2020a) reports that only some of the bio-refineries are shifting towards producing ethanol[2] for sanitizers to prevent the spread of the pandemic Coronavirus Disease (COVID-19). Therefore, to have the collaboration of all bio-refineries, the tariff for blending US bioethanol with gasoline, TL, is quite important (Ghahremanlou and Kubiak 2020d);

- Blend Wall (BW) – The highest amount of bioethanol (e.g., 10%) blended with each gallon of gasoline to meet the demand for fuel in the US is called Blend Wall (BW) (Renewable Fuels Association 2015). Under the US Clean Air Act 1963 (CAA), all light vehicles are permitted to consume a fuel consisting of up to 10% bioethanol blended with gasoline (referred to as E10). Only Flex-Fuel Vehicles (FFVs) are allowed to consume up to 85% bioethanol blended with gasoline. Specific intermediate blends, e.g., 15% bioethanol blended with gasoline (E15), can be distributed in the market under certain circumstances, e.g., vehicle models manufactured later than 2000, by waiving the CAA. In general, only E10 is consumed in the US (Yacobucci 2010).

The SPSC has been studied by Andersen et al. (2013); Kazemzadeh and Hu (2013); Ghahremanlou and Kubiak (2020c); Kazemzadeh and Hu (2015); Ghahremanlou and Kubiak (2020d), to the best of our knowledge. Andersen et al. (2013) develop two models: (1) at a macro level, to conduct research on the investment required to form the SPSC in different

[2]We reserve the word "ethanol", when it is referred to as an ingredient in sanitizers, which require a higher grade of alcohol relative to bioethanol as a fuel additive, in this paper.

regions of the US, and (2) at a micro level, to find out the fuel distribution (bioethanol-gasoline blended) within a state. Although including uncertainties inherent in the BSC (making it closer to reality) and expected profit maximization objective function (illustrating the business feasibility) in the model is beneficial (Yue et al. 2014; Meyer 2007; Awudu and Zhang 2012), their model is a deterministic cost minimization. Kazemzadeh and Hu (2013) study the SPSC by proposing two models: (1) expected profit, and (2) Conditional Value-at-Risk (CVaR) of expected profit. Later on, they extend their models in Kazemzadeh and Hu (2015) to run a computational experiment, including nine policy scenarios, to evaluate the impact of RFS2 and TCL on the SPSC. In both of their papers, they emphasize two issues: the importance of new efficient algorithms for solving the real-life SPSC optimization problems, and including government policies in the models. Ghahremanlou and Kubiak (2020c) and Ghahremanlou and Kubiak (2020d) address these gaps respectively by developing a speedy algorithm with an expected profit maximization objective function for regular economic conditions and conducting a computational experiment including RFS2, TCL, TCI, TL, TI, and BW. The creation of SPSC is a high risk business venture due to the inherent degree of uncertainty (Behrenbruch et al. 1989; Committee on Energy and Natural Resources 2007). The uncertainty is rooted in several issues, e.g., taxes and tariffs (Yanting and Liyun 2011). Therefore, risk management, which is defined as, "a scientific management method to identify, measure and analyze risk and on this basis to deal effectively with risk, to achieve maximum security at minimum cost", is of importance, especially when risk increases during economic crises (Yanting and Liyun 2011). However, there is no risk averse model, including all the supporting government policies, for the SPSC management, although currently COVID-19 and the Saudi Arabia-Russia Oil Price War have created economic catastrophe. Therefore, this paper addresses this gap by extending the risk neutral model proposed by Ghahremanlou and Kubiak (2020c) for a normal economic situation, to build a robust SPSC by hedging it against financial risks. Additionally, we conduct a case study using the risk averse model for 22,050 policy scenarios and compare the results with the risk neutral model to completely reveal the significance of this study and identify strategic investment decisions resilient to both risk preferences, meaning the decisions can withstand economic crises.

This paper applies Conditional Value-at-Risk (CVaR) to hedge the investment in the SPSC against financial risks, as it is a great match for two-stage stochastic multi-echelon location-allocation problems like the current one at hand (Rockafellar and Uryasev 2000; Ghahremanlou and Kubiak 2020c; Rockafellar and Uryasev 2002a). CVaR has properties, e.g., convexity, that makes it appropriate for optimization (Pflug 2012). For its applications in energy, see Gebreslassie et al. (2012b); Carneiro et al. (2010), forestry, see Alonso-Ayuso et al. (2018); Mansoornejad et al. (2013), and healthcare, see Dehlendorff et al. (2010); He et al. (2019). Although CVaR is mostly applied for minimization objective functions (Uryasev 2000), it can be also used for maximization objective functions (Ogryczak and Ruszczynski 2002; Kazemzadeh and Hu 2013), as in this paper.

In summary our contributions are: (1) developing a risk averse mathematical programming model, employing CVaR of expected profit as an objective function; (2) obtaining the value of CVaR of expected profit for each policy scenario; (3) determining minimum subsidy that government must provide to guarantee the SPSC will perform during economic crisis; (4) identifying the policy scenarios which results in 100% energy independence; (5) specifying the policy scenarios that lead the bio-refineries toward utilizing their capacities for producing sanitizers to combat the COVID-19 pandemic; (6) uncovering the social impact of each policy scenario; (7) providing recommendations to the investors for robust strategic investment opportunities during economic crisis; (8) deriving the policy scenarios which result in most environmentally friendly fuel, viable business conditions, and energy security; and (9) we impart the importance of using CVaR of expected profit during economic crisis by comparing the results of this risk averse study with the risk neutral of Ghahremanlou and

Kubiak (2020d), and provide strategic investment decisions resilient to economic crises.

The rest of this paper is organized as follows: Section 4.2 describes the problem at hand. Mathematical programming model for this problem is developed in Section 4.3; The data for the case study and computational experiments are provided in Section 4.4 and its Subsection 4.4.1; Section 4.5 analyzes the results of the case study and provide some recommendations for the government and industry; we clarify the significance of this study more by comparing the results of this study with Ghahremanlou and Kubiak (2020d), and provide further insights for policy makers and investors, in Section 4.6; we conclude our findings and provide some directions for further research in Section 4.7.

4.2 Problem Statement

In this paper we maximize the CVaR of expected profit for the problem stated in Ghahremanlou and Kubiak (2020c) which we concisely explain below.

The SPSC consists of: Harvesting Sites, Refineries, Gasoline Importers, Bio-refineries, Bioethanol Exporters, Bioethanol Importers from other states and abroad, Blending Sites, and Distribution Centers, see Figure 4.1. The aim of the SPSC is to meet the demand for fuel in a state of US by producing cellulosic bioethanol and blending with gasoline, while complying with government policies: RFS2, TCL, TCI, TI, TL, and BW.

The center of each county i is the location for its harvesting site and distribution center. The center of each county is also a potential location for setting up bio-refineries and blending sites with different capacities. The flow between each two members in the SPSC located in any county is allowed, following the production flow given in Figure 4.1. Transportation is done by truck throughout the entire model, and has fixed and variable distance costs.

After solving the maximization of the CVaR of expected profit to the optimality, we would plug the optimal solution into the secondary objective function, the expected number of

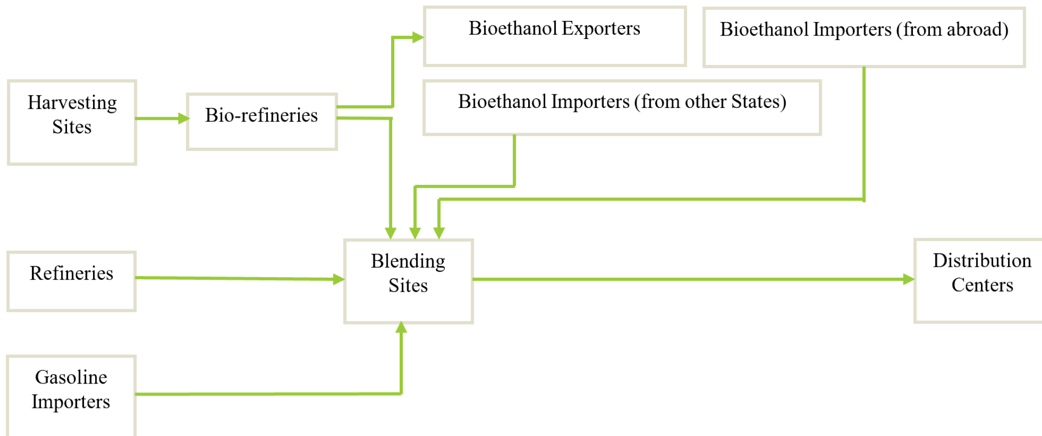


Figure 4.1: Sustainable Petroleum Supply Chain Network

jobs created in the state within the 30 year lifetime of the project, to measure the social perspective of creating the SPSC.

4.3 Formulation of Models

In this section we develop the mathematical model for our stated two-stage stochastic multi-echelon location-allocation problem.

4.3.1 CVaR of Expected Profit Maximization Objective Function

By definition of CVaR, see Ogryczak and Ruszczynski (2002), for the expected profit objective function, L_1, the CVaR of expected profit maximization objective function is as follows:

$$\max CVaR_{1-\xi}(L_1) = \zeta - \frac{1}{\xi} \cdot \sum_{s \in S} \omega_s \cdot \upsilon_s \tag{4.1}$$

where ζ and υ_s are respectively unrestricted and non-negative variables added to the model due to linearization of the objective function, $(1-\xi) \in [0,1]$ is $(1-\xi)$–quantile of the random profit, and ω_s is the probability of scenario $s \in S$.

4.3.2 Expected Number of Jobs Created Maximization Objective Function

The expected number of jobs created, L_2, in the state within 30 years lifetime of the SPSC, is generated by: (1) construction of new facilities, (2) daily operations of these facilities, and (3) transportation from/to these facilities. For the purpose of this objective function, we borrow equation (80) along with equations (74)-(78) from Ghahremanlou and Kubiak (2020c). Given the similarity of two studies, Section 4.6 illustrates the important difference in L_2, which occurs due to risk averse approach.

4.3.3 Constraints

Constraints (4.2)-(4.3) are required due to linearization of CVaR. This makes it computationally easier to solve (for details see Ogryczak and Ruszczynski (2002)).

$$\upsilon_s \geq \zeta - L_{1s}, \qquad \forall s \in S \tag{4.2}$$

$$\upsilon_s \geq 0, \qquad \forall s \in S \tag{4.3}$$

where L_{1s} is the expected profit L_1 for scenario $s \in S$. For the rest of the constraints, please see Ghahremanlou and Kubiak (2020c), components (61)-(73) and component (79) of expected profit objective function, for scenario $s \in S$, and constraints (34)-(60).

4.4 Case Study

The US stands as the largest global corn stover producer (U.S. Department of Energy 2011; Gupta and Verma 2015). Therefore, we consider corn stover as the feedstock in this paper. Iowa and Nebraska have greatest bioethanol nameplate capacity and operating production in the country (Renewable Fuels Association 2010), due to their geographical positions (Wilhelm et al. 2007). There are several papers focused on BSC in Iowa, see Li et al. (2014), Li and Hu (2014), Li et al. (2015), Zhang and Hu (2013), and Shah (2013), although only Ghahremanlou and Kubiak (2020d), with which we will compare our results, has exclusively studied Nebraska. Therefore, we consider the State of Nebraska with its 93 counties in this paper. By Kazemzadeh and Hu (2015), $\xi = 20\%$, the CVaR parameter. This value might be appropriate for economic crises like the current one resulted from COVID-19 and the 2020 Saudi Arabia-Russia Oil Price War, since it will ensure that with a probability of $100\% - \xi = 100\% - 20\% = 80\%$ the investors at least obtain the optimal expected profit. For the rest of the data, see Ghahremanlou and Kubiak (2020d).

4.4.1 Design of Computational Experiments

As we mentioned in Section 4.2, we consider all the policies:

1. Tax Credit for Local bioethanol blended with gasoline ($TCL = \eta \cdot T$, $\forall \eta \geq 0$);

2. Tax Credit for Imported bioethanol from abroad blended with gasoline ($TCI = \theta \cdot \overline{T}$, $\forall \theta \geq 0$);

3. Tariff for Local bioethanol blended with gasoline ($TL = -\eta \cdot T$, $\forall \eta \leq 0$);

4. Tariff for Imported bioethanol from abroad blended with gasoline ($TI = -\theta \cdot \overline{T}$, $\forall \theta \leq 0$);

5. RFS2 mandate for cellulosic bioethanol ($\beta \cdot \overline{\overline{R}}$);

6. Blend Wall (α);

where $T = 0.45$ and $\overline{T} = 0.54\ \frac{\$}{\text{gal}}$, and η, θ, β, and α are coefficients that help us to create different policy combinations:

- $\eta = -4.77 + 0.4 \cdot k, \forall k = 0, 1, ..., 23;$
- $\theta = -3.98 + 0.4 \cdot k, \forall k = 0, 1, ..., 19;$
- $\beta = 0.3 \cdot k, \forall k = 0, 1, ..., 12;$
- $\alpha = 10\%, 15\%, 85\%;$

also, we add the values 3.76, 4.78 and 3.98 to the discretized sets of β,η and θ respectively (Ghahremanlou and Kubiak 2020d). This results in $3 \cdot 14 \cdot 25 \cdot 21 = 22,050$ different policy scenarios. Each optimization problem with a policy scenario includes of 1,118 continuous variables, 2,520 binary variables, and 2,152 constraints. The model is coded in Python 2.7 (Python Software Foundation 2001), and it is solved to optimality using Gurobi 7.0 (Gurobi Optimizer LLC. 2008). Both the software are installed on a Dell computer with an Intel Core i5-2400 3.10 GHz CPU and 8 GB RAM.

4.5 Analysis of Results, and Recommendations

Bairamzadeh et al. (2016) emphasize the significance of studies within the sustainability framework, economic, environmental, and social perspectives. Therefore, in this section, we report on these three perspectives of the SPSC, created in response to the policy change. We consider $CVaR_{1-\xi}(L_1)$ as the primary objective function and solve it to the optimality for both the minimum and maximum transportation distance cases, which will generate optimal solutions X_{min} and X_{max} respectively. We call X_{min} and X_{max} respectively the best case and the worst case. Then, we plug $X_{\min}$ and $X_{\max}$ in L_2 to obtain $L_2(X_{\min})$ and $L_2(X_{\max})$ respectively (Ghahremanlou and Kubiak 2020c).

4.5.1 Economic Perspective

The economic activities have a direct relation with the standard of living. Steckel (2002) shows that during the 1970s oil crisis and its after shocks in the 1980s, the Gross Domestic Product (GDP) per capita, which reflects economic conditions, fell drastically in US. Therefore, it is very important to ensure top performance of the SPSC.

Figures 4.2 and 4.3 show the maximum CVaR of expected profit, $CVaR_{1-\xi}(L_1)$, that investors on the SPSC can gain in the best case, $CVaR_{1-\xi}(L_1(X_{\min}))$, and the worse case, $CVaR_{1-\xi}(L_1(X_{\max}))$ respectively. According to each plot, α, β, θ, and η influence on $CVaR_{1-\xi}(L_1(X_{\min}))$ and $CVaR_{1-\xi}(L_1(X_{\max}))$.

A side-by-side examination of plots (a) and (b), (c) and (d), (e) and (f) illustrates that for any α, θ, and η the $CVaR_{1-\xi}(L_1)$ decreases when β, represented by the colorbar, increases (as the back views have yellow color, which represents highest values of β, and the front views have blue color, which represents lowest values of β).

The comparison of the two figures for different α (e.g., plots (a) in Figures 4.2 and 4.3 for $\alpha = 10\%$) demonstrates that $CVaR_{1-\xi}(L_1(X_{\min}))$ and $CVaR_{1-\xi}(L_1(X_{\max}))$ follow the same pattern, however, for any α, β, θ, and η, $CVaR_{1-\xi}(L_1(X_{\min})) \geq CVaR_{1-\xi}(L_1(X_{\max}))$.

For any α, β, θ, and η, to have a more clear perspective on the difference between $CVaR_{1-\xi}(L_1(X_{\min}))$ and $CVaR_{1-\xi}(L_1(X_{\max}))$, we define the following indices:

1. $CVaRMaxD^{\alpha} = \max_i \{CVaR_{1-\xi}(L_1(X_{\min}(\alpha,i))) - CVaR_{1-\xi}(L_1(X_{\max}(\alpha,i)))\}$;
2. $CVaRMinD^{\alpha} = \min_i \{CVaR_{1-\xi}(L_1(X_{\min}(\alpha,i))) - CVaR_{1-\xi}(L_1(X_{\max}(\alpha,i)))\}$;

3. $CVaRAD^{\alpha} = \frac{\sum_{i=1}^{i=7350} \left[CVaR_{1-\xi}(L_1(X_{\min}(\alpha,i))) - CVaR_{1-\xi}(L_1(X_{\max}(\alpha,i)))\right]}{7350};$

being the maximum, minimum, and average difference in millions of dollars respectively. The $X_{\min}(\alpha,i)$ and $X_{\max}(\alpha,i)$ are the optimal solutions for the best and the worst case respectively with $\alpha = 10\%, 15\%$ and 85%, and the i-th combination of β, θ, and η for $i = 1,2,...,7350$; the 7350 is the number of combinations of β, θ, and η for any α, $14 \cdot 25 \cdot 21 = 7350$, see Section 4.4.1. By index number one, $CVaRMaxD^{10\%} = 153.058$, $CVaRMaxD^{15\%} = 188.529$, and $CVaRMaxD^{85\%} = 619.402$; by the second index

$$CVaRMinD^{10\%} = CVaRMinD^{15\%} = CVaRMinD^{85\%} = 82.356;$$

and finally by the third index

$$CVaRAD^{10\%} = 120.164, CVaRAD^{15\%} = 138.011, \text{ and } CVaRAD^{85\%} = 347.463$$

The three plots in red, blue and green in Figures 4.2 (g) and 4.3 (g) are respectively the three projections of $CVaR_{1-\xi}(L_1(X_{\min}))$ and $CVaR_{1-\xi}(L_1(X_{\max}))$, for $\alpha = 10\%$, 15% and 85%, fixed β and θ, and variable η. These plots show for any β, η, and θ, with increasing α, $CVaR_{1-\xi}(L_1)$ will increase. To have an idea about the growth rate we define:

- $CVaRMaxP_1^{\alpha_1\alpha_2} = \max_i\{CVaR_{1-\xi}(L_1(X_{\max}(\alpha_2,i))) - CVaR_{1-\xi}(L_1(X_{\max}(\alpha_1,i)))\};$
- $CVaRMaxP_2^{\alpha_1\alpha_2} = \max_i\{CVaR_{1-\xi}(L_1(X_{\min}(\alpha_2,i))) - CVaR_{1-\xi}(L_1(X_{\min}(\alpha_1,i)))\};$
- $CVaRMinP_1^{\alpha_1\alpha_2} = \min_i\{CVaR_{1-\xi}(L_1(X_{\max}(\alpha_2,i))) - CVaR_{1-\xi}(L_1(X_{\max}(\alpha_1,i)))\};$
- $CVaRMinP_2^{\alpha_1\alpha_2} = \min_i\{CVaR_{1-\xi}(L_1(X_{\min}(\alpha_2,i))) - CVaR_{1-\xi}(L_1(X_{\min}(\alpha_1,i)))\};$

resulting in

- $CVaRMaxP_1^{10\%15\%} = 2,772.261$; $CVaRMaxP_1^{15\%85\%} = 38,893.017$;

- $CVaRMaxP_2^{10\%15\%} = 2,807.946$; $CVaRMaxP_2^{15\%85\%} = 39,311.080$;
- $CVaRMinP_1^{10\%15\%} = 0$; $CVaRMinP_1^{15\%85\%} = 0$;
- $CVaRMinP_2^{10\%15\%} = 0$; and $CVaRMinP_2^{15\%85\%} = 0$ millions of dollars, in the experiments.

The $CVaRMinP_1^{\alpha_1\alpha_2} = CVaRMinP_2^{\alpha_1\alpha_2} = 0$ is obtained for those policy combinations in which bioethanol is not blended with gasoline, $B^\alpha = 0$, see equation (4.4) and Figure 4.2. Therefore, whenever bioethanol is blended with gasoline, $B^\alpha \neq 0$, see equation (4.4) and Figure 4.2, the growth of α results in growth of $CVaR_{1-\xi}(L_1)$.
Also, whenever bioethanol is blended with gasoline, $B^\alpha \neq 0$, see equation (4.4) and Figure 4.2, $CVaR_{1-\xi}(L_1)$ will increase if: (1) for any α, β, and θ, η increases; and (2) for any α, β, and η, θ increases.

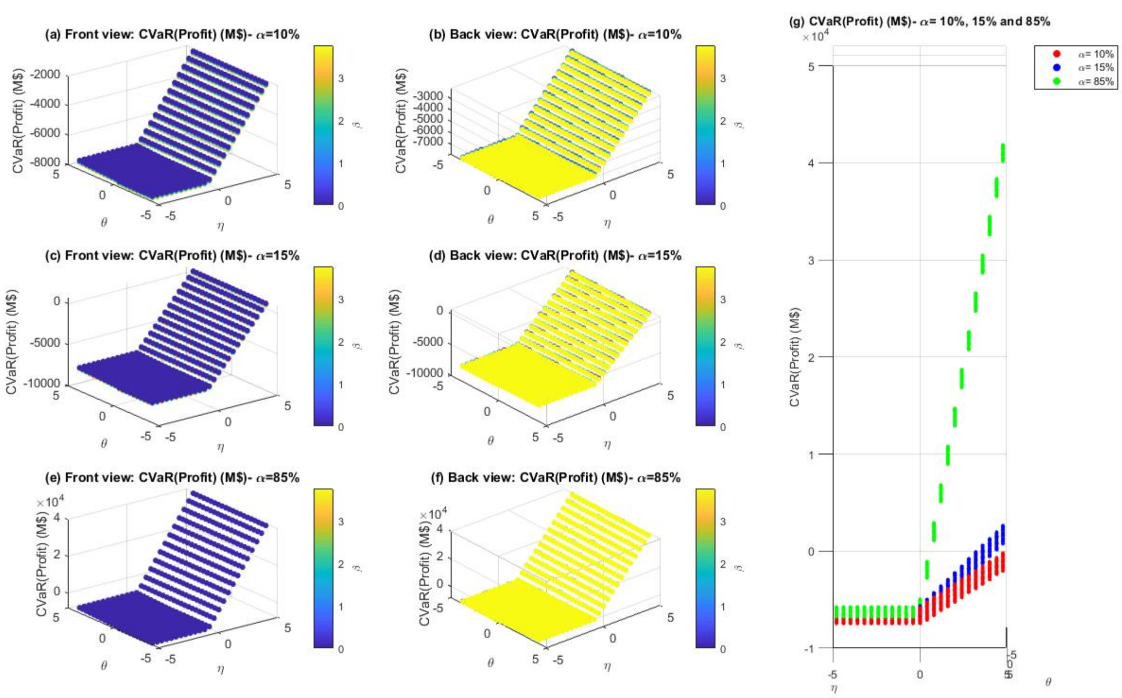


Figure 4.2: $CVaR_{1-\xi}(L_1(X_{\min}))$, $\alpha = 10\%, 15\%$ and 85%

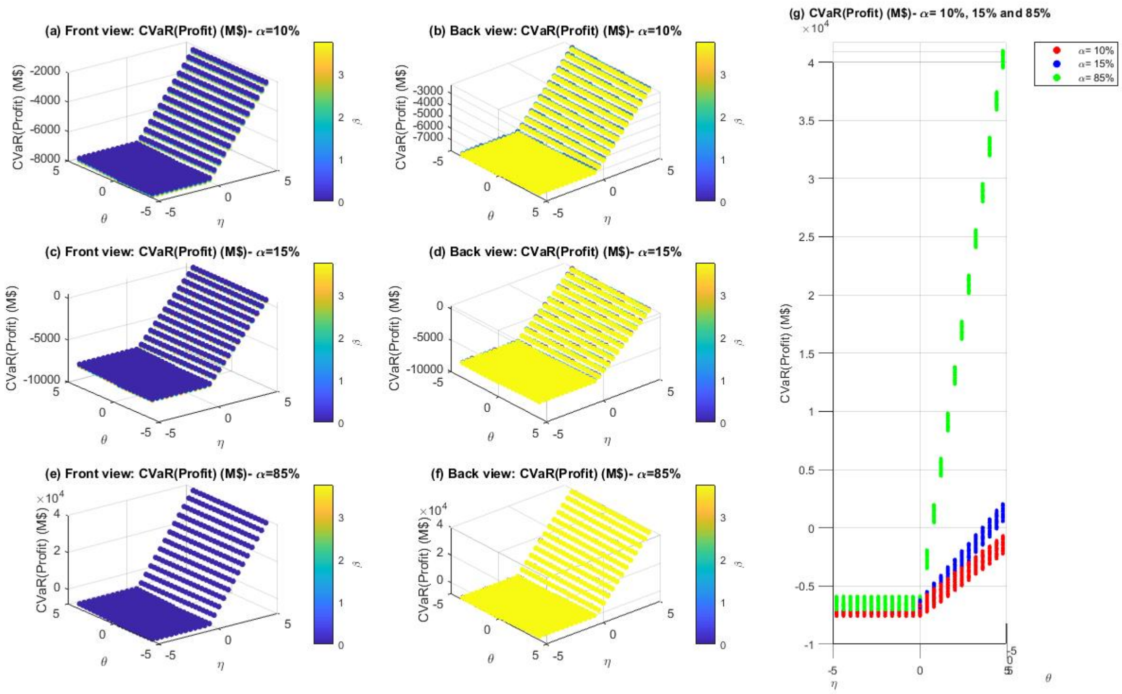


Figure 4.3: $CVaR_{1-\xi}(L_1(X_{\max}))$, $\alpha = 10\%, 15\%$ and 85%

Given the leading role of government for the SPSC, a vital element of economy, it is quite important to find out the minimum financial support, here in terms of tax credit, that will rescue the SPSC from the bankruptcy. Therefore, we define $Minimum\ \eta(\alpha, \beta, \theta)$, which is the minimum η, if any, such that $CVaR_{1-\xi}(L_1(X_{\min})) > 0$ (or $CVaR_{1-\xi}(L_1(X_{\max})) > 0$) for given α, θ, and β. Table 4.1 illustrates the $Minimum\ \eta(\alpha, \beta, \theta)$ for all policy scenarios. The $Minimum\ \eta(\alpha, \beta, \theta)$ is insensitive to θ and often to β (except when $\alpha = 15\%$ in the best case), so they are being omitted from Table 4.1. For $\alpha = 10\%$, the $Minimum\ \eta(\alpha, \beta, \theta)$ does not exist as $CVaR_{1-\xi}(L_1) < 0$, for the best and worst case. For $\alpha = 85\%$, the $Minimum\ \eta(\alpha, \beta, \theta) = 0.82$, equivalent to $TCL = 0.82 \cdot 0.45 = 0.369\ \frac{\$}{\text{gal}}$ tax credit for US bioethanol blended with gasoline. The $Minimum\ \eta(\alpha, \beta, \theta) = 4.78$ in the worst case, equivalent to $TCL = 4.78 \cdot 0.45 = 2.151\ \frac{\$}{\text{gal}}$ tax credit for US bioethanol blended with gasoline, while in the best case it is 4.42, equivalent to $TCL = 4.42 \cdot 0.45 = 1.989\ \frac{\$}{\text{gal}}$ tax credit for US bioethanol blended with gasoline, and 4.78 for $\beta \in [0, 2.1]$ and $\beta \in [2.4, 3.76]$ respectively, for $\alpha = 15\%$; the latter shows reducing *Minimum* $\eta(\alpha, \beta, \theta)$ from 4.78 to 4.42 requires reducing β. Furthermore, if the government wants to use its minimum budget, $TCL = 0.369 \frac{\$}{\text{gal}}$, while creating SPSCs that have positive CVaR of expected profit, it must increase the Blend Wall, α, to 85%.

	Minimum $\eta(\alpha,\beta,\theta)$	
α	The worst case	The best case
10%	–	–
15%	4.78	$\begin{cases} 4.42 & if \quad \beta \in [0, 2.1] \\ 4.78 & if \quad \beta \in [2.4, 3.76] \end{cases}$
85%	0.82	0.82

Table 4.1: *Minimum* $\eta(\alpha, \beta, \theta)$ for the best case and the worst case, $\alpha = 10\%, 15\%$ and 85%

4.5.2 Environment Perspective

Research shows global warming affects different dimensions of life, see Vicente-Serrano et al. (2020); Ahima (2020); Hunt et al. (2020). The SPSC, made up of cellulosic bioethanol, the most environmentally friendly bioethanol discovered yet, is evolved in response to the government policies to help toward the combat with global warming. Therefore, to find out how environmentally friendly a fuel is, we calculate B^{α}, as the average amount of bioethanol blended with gasoline in all the 36 scenarios of stochastic programming, for each policy scenario (Ghahremanlou and Kubiak 2020d):

$$B^{\alpha} = \left(\frac{\sum_{s=1}^{36} \frac{e_s + h_s + k_s}{D_s}}{36} \right) \cdot 100. \tag{4.4}$$

Figure 4.4 shows the values of B^{α}, for the best and worst case, for any α, β, θ and η. Each plot (a) to (f) in Figure 4.4 consists of three main segments: (1) no bioethanol is blended with gasoline, $B^{\alpha} = 0$, for $\eta \in [-4.78, -0.38]$ and $\theta \in [-3.98, -0.38]$; (2) bioethanol is blended to reach the maximum permitted, $B^{\alpha} = \alpha$, for any η and $\theta \in [0.02, 3.98]$; and (3) bioethanol is blended with gasoline although it is not capped, $0 < B^{\alpha} < \alpha$, for $\eta \in [0.02, 4.78]$ and $\theta \in [-3.98, -0.38]$. The first two segments, $B^{\alpha} = 0$ or α, are insensitive to β, but $0 < B^{\alpha} < \alpha$ is sensitive to it. The $B^{\alpha} = 0$, although there is bioethanol production in the best case, see Tables 4.2 and 4.3; this implies that produced bioethanol is sold to exporters. We observe that if the government wants to stop blending bioethanol with gasoline and use it for other purposes, e.g., producing sanitizers to control the spread rate of Coronavirus Disease (COVID-19), Tariffs for local bioethanol and imported bioethanol blended with gasoline must respectively be at least $TL \geq 0.38 \cdot 0.45 = 0.171 \ \frac{\$}{\text{gal}}$ and $TI \geq 0.38 \cdot 0.54 = 0.205 \ \frac{\$}{\text{gal}}$. Our results show that only foreign bioethanol is blended with gasoline to reach Blend Wall α, for $\eta \in [-4.78, -0.38]$ and $\theta \in [0.02, 3.98]$. This might be a good solution from an environmental perspective, but certainly not from an energy security perspective. To have only US bioethanol blended with gasoline, although it would not result in $B^{\alpha} = \alpha$ due to insufficient corn stover production in the US, Tax Credit for local bioethanol blended with gasoline and Tariff for blending foreign bioethanol with gasoline must respectively be at least $TCL \geq 0.02 \cdot 0.45 = 0.009 \ \frac{\$}{\text{gal}}$ and $TI \geq 0.38 \cdot 0.54 = 0.205 \ \frac{\$}{\text{gal}}$. For $TCL \geq 0.02 \cdot 0.45 = 0.009 \ \frac{\$}{\text{gal}}$, Tax Credit for local bioethanol blended with gasoline, and $TCI \geq 0.02 \cdot 0.54 = 0.01 \ \frac{\$}{\text{gal}}$, Tax Credit for local bioethanol blended with gasoline, US bioethanol and foreign bioethanol are blended with gasoline which results in $B^{\alpha} = \alpha$. Bioethanol is blended with gasoline for any policy scenario, with a minimum Tax Credit for US bioethanol blended with gasoline being $TCL \geq 0.009 \ \frac{\$}{\text{gal}}$, although, recall that to have an investment in the SPSC with positive CVaR of expected profit, it is required to have a minimum Tax Credit for US bioethanol blended with gasoline to be $TCL \geq 2.151 \ \frac{\$}{\text{gal}}$, see Section4.5.1.

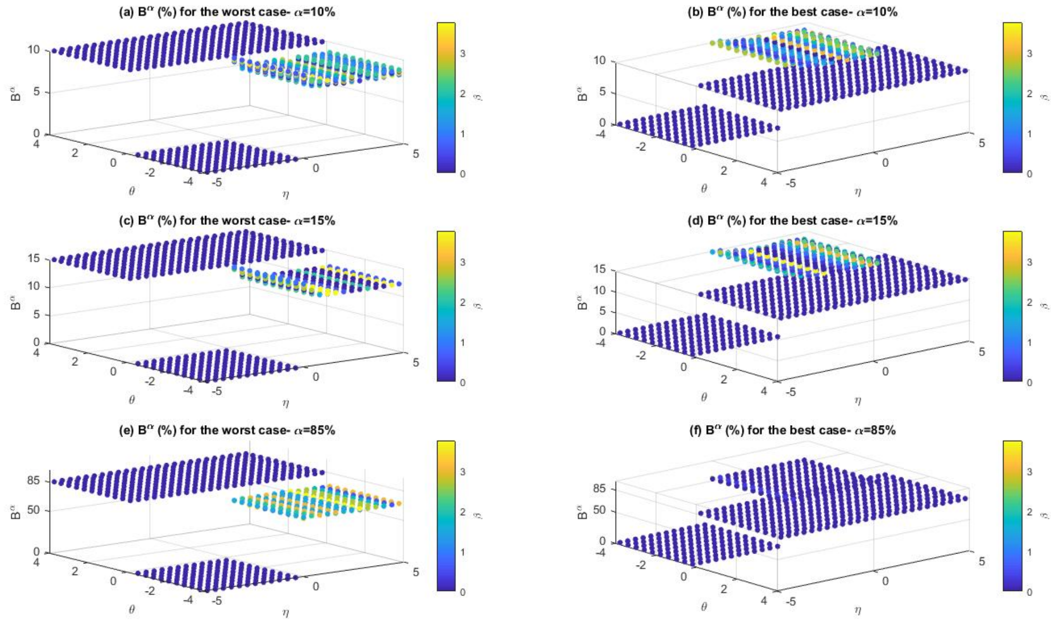


Figure 4.4: B^{α} for the best and worst case, $\alpha = 10\%, 15\%$ and 85%

4.5.3 Social Perspective

The social dimension of the SPSC, more particularly rural area development due to the BSC, has been a matter of importance since the beginning and has captured the attention of researchers, see You et al. (2012); You and Wang (2011). The current COVID-19 and the 2020 Saudi Arabia-Russia Oil Price War have impacted the SPSC, and consequently the farmers (Shearer 2020). Furthermore, the RFS2 waiver has added to the anger of the farmers (Pamuk and Singh 2020). Therefore, to provide the US policy makers some insights, we represent the expected number of jobs created in Nebraska over 30 years, in the best case, $L_2(X_{\min})$, and the worst case, $L_2(X_{\max})$ for any policy scenarios, meaning any α, β, η, and θ in Figure 4.5. We observe $L_2(X_{\min})$ and $L_2(X_{\max})$ are often sensitive to α, β, η, and θ. This reflects the impact of the amount of bioethanol blended with gasoline (see Figure 4.4), the number of bio-refineries and blending sites (see Tables 4.2 and 4.3) on L_2.

For any β, η, and θ, increasing α will not result in decreasing L_2. For any α, $\eta \in [-4.78, -0.38]$, and $\theta \in [-3.98, -0.38]$, the L_2 is insensitive to β ($L_2(X_{\max}) = 43215$ and $L_2(X_{\min}) = 37323$).

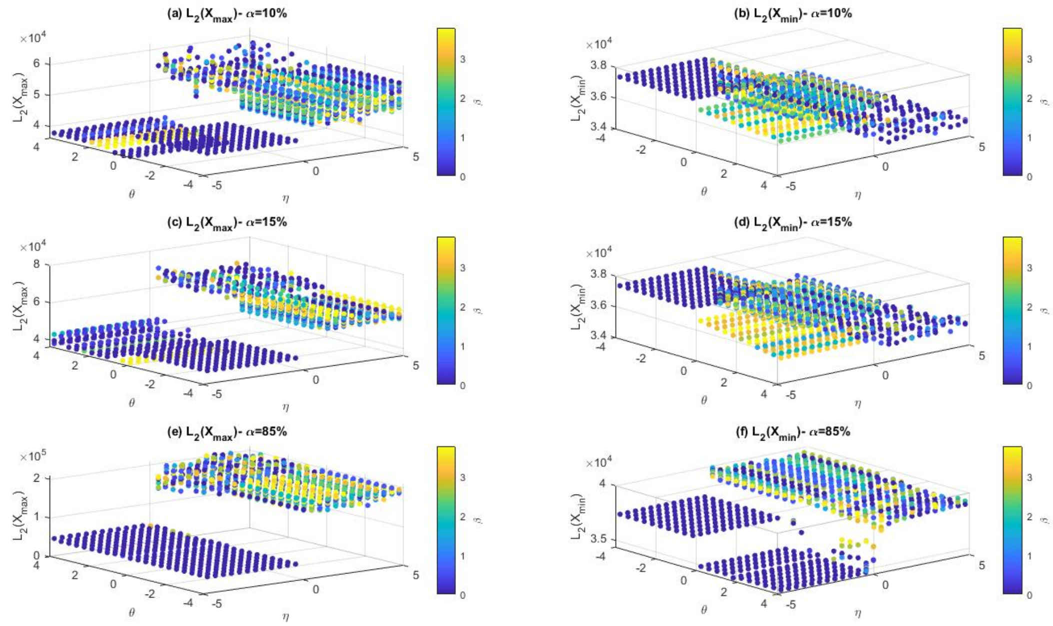


Figure 4.5: Number of expected jobs for the best, $L_2(X_{\min})$, and worst case, $L_2(X_{\max})$, $\alpha = 10\%, 15\%$ and 85%

4.5.4 Further Strategic and Managerial Insights

The strategic decisions in the SPSC are often made for long term periods, e.g., 5-30 years (Sahebi et al. 2014b; Kazemzadeh and Hu 2015). The most important strategic decisions concern the numbers, locations and capacities of the facilities in the SPSC, especially in the current situations in which the oil refineries and bio-refineries are shutting down (see Section 4.1). Therefore, we report on these issues for any government policy scenarios, and most robust decisions in Sections 4.5.4.1 and 4.5.4.2.

4.5.4.1 For $\alpha = 10\%$ and 15%

Table 4.2, for α, β, η, and θ, in the best and worst case, shows (1) number of bio-refineries, with capacity levels 1, 2, and 3 respectively being r_1, r_2, and r_3; and (2) number of blending sites, with capacity levels 1, 2, 3, 4, 5, and 6 respectively being b_1, b_2, b_3, b_4, b_5, and b_6. The number of bio-refineries are not sensitive to β, and sensitive to θ only if $\eta = 0.02$. Thus they are omitted from the table where they have no impact. Number of blending sites are insensitive to β, except b_1 in the worst case, so it is deleted from the table. We derive the following observations which are insensitive to the best and worst case:

- *Bio-refineries.* For $\eta \in [0.42, 4.78]$ or ($\eta = 0.02$ and $\theta \notin [0.02, 3.98]$), York county, possessing the maximum amount of corn stover in Nebraska, is the most robust location for setting up a bio-refinery with capacity $772,151.89 \frac{MT}{\text{y}}$, considering capacity extension to $2,316,455.67 \frac{MT}{\text{y}}$, if need be.

- *Blending sites.* For $\eta \in [0.42, 4.78]$, the most robust decisions are setting up a blending site (1) with capacity $182.95 \frac{M\text{gal}}{\text{y}}$ in Douglas county, demanding maximum amount of fuel in Nebraska, considering capacity extension to $402.49 \frac{M\text{gal}}{\text{y}}$, if need be; (2) with capacity $109.77 \frac{M\text{gal}}{\text{y}}$ in Lancaster county, demanding second maximum amount of fuel; and (3) with capacity $36.59 \frac{M\text{gal}}{\text{y}}$ in Hall county, considering capacity extension to $402.49 \frac{M\text{gal}}{\text{y}}$, if need be.

- *Other insights.* With increasing $\alpha = 10\%$ to 15%, in the worst/best case: (1) the number and capacity of bio-refineries are not decreasing, for any β, η, and θ, and (2) likewise, the number and capacity of blending sites are not decreasing, for $\eta \in [0.42, 4.78]$, regardless of β and θ. The number and capacity of bio-refineries are more in the best case, relative to the worst case. This implies the importance of feedstock transportation cost. For $\eta \in [0.42, 4.78]$, total number and capacity of blending sites in the worst case are respectively over 11 times and 2 times than the best case. The policies resulting in positive expected profit, and most environmentally friendly fuel are, Blend Wall $\alpha = 15\%$, Tax Credit for local bioethanol and foreign bioethanol respectively to be at least $TCL \geq 4.78 \cdot 0.45 = 2.151 \ \frac{\$}{\text{gal}}$ and $TCI \geq 0.02 \cdot 0.54 = 0.01 \ \frac{\$}{\text{gal}}$. However, Nebraska will be totally independent from foreign bioethanol. To have Nebraskan independence from foreign bioethanol, positive expected profit, and most environmentally friendly fuel, Tax Credit for local bioethanol and Tariff for foreign bioethanol must respectively be $TCL \geq 2.151 \ \frac{\$}{\text{gal}}$ and $TI \geq 0.38 \cdot 0.54 = 0.205 \ \frac{\$}{\text{gal}}$. Figure 4.5 illustrates $TCL \geq 2.151 \ \frac{\$}{\text{gal}}$ results in high expected number of jobs.

4.5.4.2 For $\alpha = 85\%$

Table 4.3 shows that the number of bio-refineries, r_1, r_2, and r_3, is not sensitive to β; also, in the best case, they are insensitive to η and θ, which are omitted from the table. Number of blending sites, b_1, b_2, b_3, b_4, b_5, and b_6, are insensitive to β, thus deleted from the table, but often sensitive to η and θ.

- *Bio-refineries.* For $\eta \in [0.42, 4.78]$, establishing a bio-refinery with capacity $772,151.89 \ \frac{MT}{\text{y}}$, considering capacity extension to $2,316,455.67 \ \frac{MT}{\text{y}}$, if need be, at York, Buffalo, and Hall counties.

- *Blending sites.* For $\eta \in [0.42, 4.78]$, establishing a bio-refinery with capacity 109.77 $\frac{M\text{gal}}{\text{y}}$ at York, Buffalo, and Hall, respectively considering capacity extension to: 182.95, 256.13, and 182.95 $\frac{M\text{gal}}{\text{y}}$, if need be, at York, Buffalo, and Hall counties.

- *Other insights.* For any β and θ, and $\eta \in [0.42, 4.78]$: (1) number of bio-refineries in the worst case is more than twice the best case, however, the total capacity of bio-refineries in the best case is more than worse case. This implies the significance of feedstock transportation cost; and (2) number of blending sites, in the worse case, is almost seven times the best case, although the total capacity of blending sites is just over twice. The policies resulting in positive expected profit, and most environmentally friendly fuel are, Tax Credit for local bioethanol and foreign bioethanol respectively be $TCL \geq 0.82 \cdot 0.45 = 0.369 \frac{\$}{\text{gal}}$ and $TCI \geq 0.02 \cdot 0.54 = 0.01 \frac{\$}{\text{gal}}$. However, Nebraska will be totally independent from foreign bioethanol. To have the State of Nebraska independent from foreign bioethanol, positive expected profit, and most environmentally friendly fuel, Tax Credit for local bioethanol and Tariff for foreign bioethanol must respectively be $TCL \geq 0.369 \frac{\$}{\text{gal}}$ and $TI \geq 0.38 \cdot 0.54 = 0.205 \frac{\$}{\text{gal}}$. Figure 4.5 illustrates $TCL \geq 0.369 \frac{\$}{\text{gal}}$ and $TCI \geq 0.01/TI \geq 0.205 \frac{\$}{\text{gal}}$ result in high expected number of jobs.

The worst case	
$\alpha = 10\%$	$\alpha = 15\%$
$r_1 = \begin{cases} 0 & if \quad \eta \in [-4.78,-0.38] \ or \\ & \eta = 0.02, \theta \in [0.02,3.98] \\ 1 & if \quad \eta \in [0.42,4.78] \ or \\ & \eta = 0.02, \theta \notin [0.02,3.98] \end{cases}$	$r_1 = \begin{cases} 0 & if \quad \eta \in [-4.78,-0.38] \ or \\ & \eta = 0.02, \theta \in [0.02,3.98] \\ 2 & if \quad \eta \in [0.42,4.78] \ or \\ & \eta = 0.02, \theta \notin [0.02,3.98] \end{cases}$
$r_2 = 0$	$r_2 = 0$
$r_3 = 0$	$r_3 = 0$
$b_1 = \begin{cases} 30 & if \quad \eta \in [0.42,4.78] \\ 32 & if \quad \eta \in [-4.78,0.02], \\ & \theta \in [0.02,3.98] \\ 34 & if \quad \eta = 0.02, \theta \in [-3.98,-0.38], \\ & \beta = 3.76 \\ 35 & if \quad \eta = 0.02, \theta \in [-3.98,-0.38], \\ & \beta \in [1.8,3.6] \\ 36 & if \quad \eta = 0.02, \theta \in [-3.98,-0.38], \\ & \beta \in [0,1.5] \\ 50 & if \quad \eta \in [-4.78,-0.38], \theta \in [-3.98,-0.38] \end{cases}$	$b_1 = \begin{cases} 29 & if \quad \eta \in [0.42,4.78] \ or \\ & \eta = 0.02, \theta \in [-3.98,-0.38] \\ 32 & if \quad \eta \in [-4.78,0.02], \\ & \theta \in [0.02,3.98] \\ 50 & if \quad \eta \in [-4.78,-0.38], \\ & \theta \in [-3.98,-0.38] \end{cases}$
$b_2 = \begin{cases} 1 & if \quad \eta \in [-4.78,-0.38], \theta \in [-3.98,-0.38] \\ 2 & if \quad \eta \notin [-4.78,-0.38], \theta \notin [-3.98,-0.38] \end{cases}$	$b_2 = \begin{cases} 1 & if \quad \eta \in [-4.78,-0.38], \\ & \theta \in [-3.98,-0.38] \\ 2 & if \quad \eta \notin [-4.78,-0.38], \\ & \theta \notin [-3.98,-0.38] \end{cases}$
$b_3 = \begin{cases} 0 & if \quad \eta = 0.02, \theta \in [-3.98,-0.38] \\ 1 & if \quad \eta \neq 0.02, \theta \notin [-3.98,-0.38] \end{cases}$	$b_3 = \begin{cases} 1 & if \quad \eta \in [-4.78,-0.38] \ or \\ & \eta = 0.02, \theta \in [0.02,3.98] \\ 2 & if \quad \eta \in [0.42,4.78] \ or \\ & \eta = 0.02, \theta \notin [0.02,3.98] \end{cases}$
$b_4 = \begin{cases} 0 & if \quad \eta \neq 0.02, \theta \notin [-3.98,-0.38] \\ 1 & if \quad \eta = 0.02, \theta \in [-3.98,-0.38] \end{cases}$	$b_4 = 0$
$b_5 = \begin{cases} 0 & if \quad \eta \notin [-4.78,-0.38], \\ & \theta \notin [-3.98,-0.38] \\ 1 & if \quad \eta \in [-4.78,-0.38], \\ & \theta \in [-3.98,-0.38] \end{cases}$	$b_5 = \begin{cases} 0 & if \quad \eta \notin [-4.78,-0.38], \\ & \theta \notin [-3.98,-0.38] \\ 1 & if \quad \eta \in [-4.78,-0.38], \\ & \theta \in [-3.98,-0.38] \end{cases}$
$b_6 = \begin{cases} 0 & if \quad \eta \in [-4.78,-0.38] \ or \\ & \eta = 0.02, \theta \in [0.02,3.98] \\ 1 & if \quad \eta = 0.02, \theta \notin [0.02,3.98] \ or \\ & \eta \in [0.42,4.78] \end{cases}$	$b_6 = \begin{cases} 0 & if \quad \eta \in [-4.78,-0.38] \ or \\ & \eta = 0.02, \theta \in [0.02,3.98] \\ 1 & if \quad \eta = 0.02, \theta \notin [0.02,3.98] \ or \\ & \eta \in [0.42,4.78] \end{cases}$
The best case ($\alpha = 10\%$ and 15%)	
$r_1 = r_2 = b_1 = b_3 = b_4 = b_5 = 0, r_3 = 3, b_2 = 1, b_6 = 2$	

Table 4.2: Strategic decisions for the best case and the worst case, $\alpha = 10\%$ and 15%

$\alpha = 85\%$	
The worst case	The best case
$r_1 = \begin{cases} 0 & if \quad \eta \in [-4.78, -0.38] \text{ or } \\ & \eta = 0.02, \theta \in [0.02, 3.98] \\ 5 & if \quad \eta = 0.02, \theta \notin [0.02, 3.98] \\ 8 & if \quad \eta \in [0.42, 4.78] \end{cases}$	$r_1 = 0$
$r_2 = 0$	$r_2 = 0$
$r_3 = \begin{cases} 0 & if \quad \eta \neq 0.02, \theta \notin [-3.98, -0.38] \\ 1 & if \quad \eta = 0.02, \theta \in [-3.98, -0.38] \end{cases}$	$r_3 = 3$
$b_1 = \begin{cases} 23 & if \quad \eta \in [0.42, 4.78], \\ 32 & if \quad \eta \in [-4.78, 0.02], \\ & \theta \in [0.02, 3.98] \\ 35 & if \quad \eta = 0.02, \theta \in [-3.98, -0.38] \\ 50 & if \quad \eta \in [-4.78, -0.38], \\ & \theta \in [-3.98, -0.38] \end{cases}$	$b_1 = 0$
$b_2 = \begin{cases} 1 & if \quad \eta \in [-4.78, -0.38], \\ & \theta \in [-3.98, -0.38] \\ 2 & if \quad \eta \in [-4.78, 0.02], \\ & \theta \in [0.02, 3.98] \\ 6 & if \quad \eta = 0.02, \theta \in [-3.98, -0.38] \\ 10 & if \quad \eta \in [0.42, 4.78] \end{cases}$	$b_2 = 1$
$b_3 = 1$	$b_3 = \begin{cases} 0 & if \quad \eta \in [-4.78, -0.38] \text{ or } \\ & \eta = 0.02, \theta \in [0.82, 3.98] \\ 3 & if \quad \eta \in [0.42, 4.78] \text{ or } \\ & \eta = 0.02, \theta \notin [0.82, 3.98] \end{cases}$
$b_4 = \begin{cases} 0 & if \quad \eta \neq 0.02, \theta \notin [-3.98, -0.38] \\ 1 & if \quad \eta = 0.02, \theta \in [-3.98, -0.38] \end{cases}$	$b_4 = \begin{cases} 0 & if \quad \eta \in [-4.78, -0.38] \text{ or } \\ & \eta = 0.02, \theta \in [0.82, 3.98] \\ 1 & if \quad \eta \in [0.42, 4.78] \text{ or } \\ & \eta = 0.02, \theta \notin [0.82, 3.98] \end{cases}$
$b_5 = \begin{cases} 0 & if \quad \eta \notin [-4.78, 0.02], \\ & \theta \notin [-3.98, -0.38] \\ 1 & if \quad \eta \in [-4.78, 0.02], \\ & \theta \in [-3.98, -0.38] \end{cases}$	$b_5 = 0$
$b_6 = 0$	$b_6 = \begin{cases} 0 & if \quad \eta \in [0.42, 4.78] \text{ or } \\ & \eta = 0.02, \theta \in [-3.98, 0.42] \\ 2 & if \quad \eta = 0.02, \theta \notin [-3.98, 0.42] \text{ or } \\ & \eta \notin [0.42, 4.78] \end{cases}$

Table 4.3: Strategic decisions for the best case and the worst case, $\alpha = 85\%$

4.6 Comparison

This section provides insights into the difference between the results and recommendations of this study and the one performed by Ghahremanlou and Kubiak (2020d). These studies have different risk tolerances, the former being risk averse and the latter being risk neutral. The comparison sheds light on two issues: (1) the importance of applying the CVaR of expected profit, relative to expected profit in the current economic slowdown, and (2) strategic investment decisions resilient to risk preferences, meaning the decisions can withstand the economic crisis.

1. *Economic Perspective* – For any given α and i being policy combination (β, θ, and η), we calculate:

   (a) maximum difference between expected profit and the CVaR of expected profit in the best case;

   (b) maximum difference between expected profit and the CVaR of expected profit in the worst case;

   (c) minimum difference between expected profit and the CVaR of expected profit in the best case;

   (d) minimum difference between expected profit and the CVaR of expected profit in the worst case;

   (e) average difference between expected profit and the CVaR of expected profit in the best case;

   (f) average difference between expected profit and the CVaR of expected profit in the worst case;

   by respectively defining:

   (a) $MaxDMin^{\alpha} = \max_{i}\{L_1(X_{\min}(\alpha,i)) - CVaR_{1-\xi}(L_1(X_{\min}(\alpha,i)))\}$;

   (b) $MaxDMax^{\alpha} = \max_{i}\{L_1(X_{\max}(\alpha,i)) - CVaR_{1-\xi}(L_1(X_{\max}(\alpha,i)))\}$;

   (c) $MinDMin^{\alpha} = \min_{i}\{L_1(X_{\min}(\alpha,i)) - CVaR_{1-\xi}(L_1(X_{\min}(\alpha,i)))\}$;

   (d) $MinDMax^{\alpha} = \min_{i}\{L_1(X_{\max}(\alpha,i)) - CVaR_{1-\xi}(L_1(X_{\max}(\alpha,i)))\}$;

   (e) $CADMin^{\alpha} = \dfrac{\sum_{i=1}^{i=7350} \left[L_1(X_{\min}(\alpha,i)) - CVaR_{1-\xi}(L_1(X_{\min}(\alpha,i)))\right]}{7350}$;

(f) $CADMax^{\alpha} = \frac{\sum_{i=1}^{i=7350} \left[L_1(X_{\max}(\alpha,i)) - CVaR_{1-\xi}(L_1(X_{\max}(\alpha,i)))\right]}{7350}$.

We derive

(a) $MaxDMin^{10\%} = 9,832.752$; $MaxDMin^{15\%} = 10,896.372$;

(b) $MaxDMin^{85\%} = 18,297.84$; $MaxDMax^{10\%} = 9,795.273$;

(c) $MaxDMax^{15\%} = 10,858.532$; and $MaxDMax^{85\%} = 18,209.965$;

in millions of dollars in our experiments, which represent the maximum amount that the CVaR of expected profit is less than the expected profit, in the best and worst case. The minimum difference between the CVaR of expected profit and the expected profit, for different α and i, in the best and worst case is: $MinDMin^{10\%} = 7,553.004$; $MinDMin^{15\%} = 7,553.004$; $MinDMin^{85\%} = 7,553.004$; $MinDMax^{10\%} = 7,533.25$; $MinDMax^{15\%} = 7,533.25$; and $MinDMax^{85\%} = 7,533.25$ in millions of dollars in our experiments. Similarly, the average difference is: $CADMin^{10\%} = 8,216.450$; $CADMin^{15\%} = 8,510.367$; $CADMin^{85\%} = 10,597.364$; $CADMax^{10\%} = 8,190.534$; $CADMax^{15\%} = 8,484.287$; and $CADMax^{85\%} = 10,547.596$ in millions of dollars in our experiments.

We observe that even if the government subsidy, Tax Credit for blending US bioethanol with gasoline (TCL), is $TCL = 4.78 \cdot 0.45 = 2.151 \frac{\$}{\text{gal}}$ the CVaR of expected profit is not positive, while the expected profit becomes positive with at least $TCL \geq 0.42 \cdot 0.45 = 0.189 \frac{\$}{\text{gal}}$, for $\alpha = 10\%$, any β, θ, and η. For $\alpha = 15\%$, regardless of other policies, if $TCL \geq 0.42 \cdot 0.45 = 0.189 \frac{\$}{\text{gal}}$ and $TCL \geq 4.78 \cdot 0.45 = 2.151 \frac{\$}{\text{gal}}$, respectively, the CVaR of expected profit, and the expected profit will be positive. Likewise, for $\alpha = 85\%$, to have both a positve CVaR of expected profit, and the expected profit, respectively, $TCL \geq 0.82 \cdot 0.45 = 0.369 \frac{\$}{\text{gal}}$ and $TCL \geq 0.02 \cdot 0.45 = 0.009 \frac{\$}{\text{gal}}$.

Furthermore, an increase in RFS2 by increasing β, may demand more TCL to have a positive CVaR of expected profit.

2. *Environment Perspective* – The amount of bioethanol blended with gasoline is sensitive to RFS2 changes in the risk averse approach, while it is not in the risk neutral approach. There are not many intermediate blends in the model with expected profit objective function, in contrast to this study with CVaR of expected profit objective function. Furthermore, in this study with minimum tariff for blending bioethanol with gasoline at $TI \geq 0.38 \cdot 0.54 = 0.205 \frac{\$}{\text{gal}}$ bioethanol is not blended with gasoline, while in the risk neutral study it must be at least $TI \geq 2.78 \cdot 0.54 = 1.501 \frac{\$}{\text{gal}}$.

3. *Social and Managerial Perspective* – In this study, in contrast to the risk neutral study, the expected number of jobs created is sensitive to RFS2. For $\alpha = 10\%$ and 15%, if $TCL \geq 0.42 \cdot 0.45 = 0.189 \frac{\$}{\text{gal}}$, in both studies, setting up a bio-refinery in Hall county that it could process the amount of corn stover from $772,151.89$ to $2,316,455.67 \frac{MT}{\text{y}}$ is robust to policy changes and transportation cost; likewise the blending site Douglas county with capacity 182.95 $\frac{M\text{gal}}{\text{y}}$, which could increase the capacity to 402.49 $\frac{M\text{gal}}{\text{y}}$, if need be. In this study the blending site at Lancaster should have 109.77 $\frac{M\text{gal}}{\text{y}}$ capacity, while in the risk neutral study, it should be able to meet the demand between 329.31 and 402.49 $\frac{M\text{gal}}{\text{y}}$. In this study the blending site at Spary county is not robust, while a blending site at Hall county with capacity 36.59 $\frac{M\text{gal}}{\text{y}}$, with potential extension to 402.49 $\frac{M\text{gal}}{\text{y}}$ is robust. For $\alpha = 85\%$, the same bio-refineries need to be set up, in both studies. The number of blending sites and their capacities are different in both the studies. The strategic investment decisions that are same in both the studies are resilient to the risk preferences; this implies that they can withstand economic crises.

4.7 Conclusions and Further Research

We studied the requirements for creating a robust SPSC during economic crisis. Following suit, we extended the risk neutral model in Ghahremanlou and Kubiak (2020c), and developed a risk averse model to hedge the SPSC against financial risks. Our model includes CVaR of annual expected profit maximization objective to study economic perspective, and the expected number of jobs created during the 30 years lifetime of the project to study the social perspective of the SPSC within a state of the US, including only cellulosic bioethanol produced from corn stover. We measure the environmental friendliness of a fuel by the average amount of bioethanol blended in it. Our model accounts for Renewable Fuel Standard 2 (RFS2), Tax Credits for US and foreign bioethanol blended with gasoline (TCL and TCI respectively), Tariffs for US and foreign bioethanol blended with gasoline (TL and TI respectively), and Blend Wall (BW). Given the supportive and leading role of government policies in the performance of SPSC, especially during economic crisis, first we provide the following conclusions:

- If $TCL \geq 0.009\ \frac{\$}{\text{gal}}$ or $TCI \geq 0.01\ \frac{\$}{\text{gal}}$, bioethanol is blended with gasoline, for fixed TCL, TCI, TL, TI, and RFS2, by increasing the BW: (1) the CVaR of annual expected profit increases; (2) the more environmentally friendly fuel is produced; and (3) the expected number of jobs created may increase, as will the number and capacity of bio-refineries and blending sites. Therefore, mandating the registration of only Flex-Fuel Vehicles, for example, or employing any other strategy to increase the BW to 85%, might be the best direction for the government to meet its goals, without much direct subsidy.

- Increasing RFS2, for fixed TCL, TCI, TL, TI, and BW: (1) reduces the CVaR of annual expected profit, which might result in bankruptcies of the SPSCs, e.g., 2018 bankruptcy of Philadelphia Energy Solutions (DiNapoli and Renshaw 2018; Simeone 2018; Stein 2018); (2) increases the amount of bioethanol blended with gasoline, whenever Tax Credit for local bioethanol blended with gasoline and Tariff for blending foreign bioethanol with gasoline are respectively at least $TCL \geq 0.009~\frac{\$}{\text{gal}}$ and $TI \geq 0.205~\frac{\$}{\text{gal}}$; (3) may increase the expected number of jobs created, although in contrast it may reduce the number of small blending sites, while not having any impact on the number and capacities bio-refineries.

- By increasing $TCL \geq 0.009~\frac{\$}{\text{gal}}$, for fixed RFS2, TCI, TI, and BW: (1) the CVaR of annual expected profit increases; (2) more environmentally friendly fuel may be produced; (3) the expected number of jobs created may increase. In contrast, by increasing TL, for fixed RFS2, TCI, TI, and BW: (1) the CVaR of annual expected profit stays the same; (2) does not influence on environmentally friendly fuel being produced; (3) the expected number of jobs created may reduce.

- By increasing $TCI \geq 0.01~\frac{\$}{\text{gal}}$, for fixed RFS2, TCL, TL, and BW: (1) the CVaR of annual expected profit increases; (2) the most environmentally friendly fuel is produced; (3) the expected number of jobs created may increase. In contrast, by increasing TI for fixed RFS2, TCL, TL, and BW: (1) the CVaR of annual expected profit stays the same; (2) environmentally friendly fuel may be produced; (3) the expected number of jobs created stays the same.

We observe that to utilize the capacity of the bio-refineries for producing sanitizers to combat Coronavirus Disease (COVID-19), Tariffs for local bioethanol and imported bioethanol blended with gasoline must respectively be at least $TL \geq 0.171~\frac{\$}{\text{gal}}$ and $TI \geq 0.205~\frac{\$}{\text{gal}}$. We conclude that if we want to hedge against financial risks during economic crisis, for example the current one resulting from COVID-19 and the Oil Price War, RFS2 will be quite important and may result in bankruptcy of the SPSC; however, this is not the case in risk neutral situations, see Ghahremanlou and Kubiak (2020d). Furthermore, we acknowledge the importance of BW, TCL, TL, TCI, and TI.

Government intervention to boost the economy by its policy leverage may not be advantageous to all the SPSCs, including refineries and bio-refineries; recall the bankruptcy of Philadelphia Energy Solutions. Therefore, creating robust SPSCs, insensitive to policy changes, will be quite important. However, we observed that to create a SPSC with a positive CVaR of annual expected profit: (1) there is a need for at least $TCL \geq 0.369\ \frac{\$}{\text{gal}}$ Tax Credit for US bioethanol blended with gasoline, for BW being 85%; (2) Tax Credit for US bioethanol blended with gasoline must be at least $TCL \geq 2.151\ \frac{\$}{\text{gal}}$, for BW being 15%; and (3) it is impossible for BW to be 10%. That being said, if $TCL \geq 2.151\ \frac{\$}{\text{gal}}$, regardless of any other policies, the robust investment decisions are: (1) setting up a bio-refinery with capacity $772,151.89\ \frac{MT}{\text{y}}$, which can process $2,316,455.67\ \frac{MT}{\text{y}}$ corn stover, if need be, at York county; and (2) establishing a blending site with capacity $36.59\ \frac{M\text{gal}}{\text{y}}$, which can meet the demand for $182.95\ \frac{M\text{gal}}{\text{y}}$ fuel, if need be, at Hall county. These investment decisions will result in producing the most environmentally friendly fuel, whenever the government considers:

1. At least $TCI \geq 0.01\ \frac{\$}{\text{gal}}$ Tax Credit for foreign bioethanol blended with gasoline, since all corn stover produced in the US is not sufficient to produce the amount of bioethanol which should reach the BW even in Nebraska; therefore, we also recommend utilizing other feedstock for producing cellulosic bioethanol;

2. To make Nebraska independent from foreign bioethanol, government must additionally consider at least $TI \geq 0.205\ \frac{\$}{\text{gal}}$ Tariff for blending foreign bioethanol with gasoline.

Comparing the results of the risk averse model in this paper with the risk neutral one in Ghahremanlou and Kubiak (2020d) reveals that during the economic crisis: (1) the SPSC requires a great deal more government subsidy to survive; RFS2 plays a critical role in producing environmentally friendly fuel; (3) for $\alpha = 10\%$ and 15%, if $TCL \geq 0.42 \cdot 0.45 = 0.189\ \frac{\$}{\text{gal}}$, setting up a bio-refinery and a blending site, respectively, at Hall county with capacity $772,151.89$ with extension capability to $2,316,455.67\ \frac{MT}{\text{y}}$, and Douglas county with capacity $182.95\ \frac{M\text{gal}}{\text{y}}$, which could increase the capacity to $402.49\ \frac{M\text{gal}}{\text{y}}$, both decisions are resilient against the two risk preferences, meaning they can withstand economic crises; and (4) for $\alpha = 85\%$, and $TCL \geq 0.189\ \frac{M\text{gal}}{\text{y}}$, setting up a bio-refinery with capacity $772,151.89\ \frac{MT}{\text{y}}$, considering capacity extension to $2,316,455.67\ \frac{MT}{\text{y}}$, if need be, at York, Buffalo, and Hall counties, is resilient to economic crises.

Solving the same model with different risk preferences is a direction for further research. Applying the model developed in this paper to other states of US may provide new insights due to different geographical situation. Applying other quantile risk methods, e.g., excess probability (see Schultz and Tiedemann (2003)), or deviation measures, e.g., expected excess (see Kristoffersen (2005)) or semideviation (see Ahmed (2006)), are other avenues for research.

The following chapter is:

Ghahremanlou, D. and W. Kubiak (2020d). An approach to studying Sustainable Crude Oil Supply Chains (SCOSCs) evolved by changing US government policies - Part I (Models). *Journal of Cleaner Production*. **Submitted**.

Chapter 5

An approach to studying Sustainable Crude Oil Supply Chains (SCOSCs) evolved by changing US government policies - Part I (Models)

Abstract Global warming and crude oil dependency have driven policymakers to lay down policies to turn the Conventional Crude Oil Supply Chain (CCOSC) into a Sustainable Crude Oil Supply Chain (SCOSC). To respond to those challenges the US, the world's largest oil user, has put in place policies to regulate bioethanol production and consumption for the past half century. Although these regulations created new opportunities, they also placed new burdens on the obligated parties. The effect of the policy change on the SCOSC is therefore important for the government, the obligated parties and related businesses to study. To that end we extend the SCOSC studied by Ghahremanlou and Kubiak (2020c) to include both first and second generation bioethanol, their import and export, and the existing infrastructure to investigate and compare SCOSCs which evolve as the re-

sult of changing government policies: Renewable Fuel Standard 2, Tax Credits for US and foreign bioethanol blended with gasoline, Tariffs for US and foreign bioethanol blended with gasoline, and Blend Wall. We approach the problem by developing an algorithm, a two-stage stochastic programming model, referred to as Extended Lean Model (ELM) in this Part I. In the accompanying Part II, Ghahremanlou and Kubiak (2020b), we conduct a case study for the State of Nebraska using the ELM. The ELM permits us to solve 21,420 alternative policy scenarios to optimality for the purpose of the study, within a reasonable time, which is impossible to achieve with other models existing in the literature. We also discuss the creation of robust SCOSCs, given the Oil War, and the shift in ethanol[2] production towards meeting critical demand for sanitizers to prevent the spread of Coronavirus Disease (COVID-19), currently a global pandemic.

5.1 Introduction

Climate change, unequal global distribution of crude oil reservoirs, and political instability of countries possessing the majority of reservoirs forced many countries to substitute oil with local renewable sources of energy (Sahebi et al. 2014a; Agarwal 2007; Yan 2012; Akgul et al. 2011). Following suit, the US, the largest oil user and producer in the world (U.S. Energy Information Administration 2020b), created policies to use bioethanol, produced from biological materials (Humbird et al. 2011; El-Naggar et al. 2014; Baeyens et al. 2015), as an additive to crude oil derived gasoline (Yacobucci 2010; Agarwal 2007; IHS Markit 2019), its main transportation fuel (U.S. Energy Information Administration 2017a). This resulted in creating an Bioethanol Supply Chain (BSC) and merging it with the Conventional Crude Oil Supply Chain (CCOSC) to form a Sustainable Crude Oil Sup-

[2]Throughout this paper we reference ethanol as an ingredient in sanitizers, which require a higher grade of alcohol relative to bioethanol as a fuel additive.

ply Chain (SCOSC). To attain environmental, economic, and social advantages of transition from CCOSC to SCOSC, well planned and implemented policies were required, otherwise the transition would have had destructive effects. An example of this is the bankruptcy of Philadelphia Energy Solutions, the largest US East coast oil refinery, which resulted in job losses in 2018 (Renshaw 2018; Willette 2018; DiNapoli and Renshaw 2018; Simeone 2018; Stein 2018) for which Renewable Fuel Standard 2 (RFS2) was blamed. To deal with this and similar cases the US administration has granted waivers to some of the refineries, an act considered to be in violation of the law (Kelly 2020). More recently, the Oil War between Saudi Arabia and Russia pushed the price of US oil down to negative for the first time in history, and could lead to the bankruptcy of hundreds of US oil companies (Egan and CNN Business 2020). Consequently, many bio-refineries are closing, while some are redirecting their production towards meeting the great demand for ethanol to produce sanitizers during COVID-19 (Voegele 2020a). Given the leading role of the government, policies to protect and guide the SCOSC in this emerging situation are critical (Almeida et al. 2020). Therefore, in this paper and its accompanying paper, Ghahremanlou and Kubiak (2020b), respectively, we propose an approach, and study the SCOSCs which evolve in response to changing policies:

- Renewable Fuel Standard 2 (RFS2) – The Energy Independence and Security Act (EISA) includes RFS2, established in 2007. According to RFS2 the obligated parties, meaning gasoline refiners and gasoline importers in the US, are supposed to blend a minimum amount of bioethanol (McPhail et al. 2011; Cornell Law School 2010), called Renewable Volume Obligation (RVO) or mandate, with their gasoline each year (Thompson et al. 2009; Duffield et al. 2008). The RFS2 categorizes the bioethanol into: (1) 1^{st} generation bioethanol with 20% Greenhouse Gas (GHG) emission reduction, e.g., bioethanol produced from corn; (2) 2^{nd} generation bioethanol with 60% GHG emission reduction, e.g., bioethanol produced from corn stover; and (3) 3^{rd} generation bioethanol with 50% GHG emission reduction, e.g., bioethanol produced from algae (Baeyens et al. 2015; Thompson et al. 2009). The 1^{st} generation is long established and commercialized, the 2^{nd} generation is recently commercialized, and 3^{rd} generation yet to be commercialized. Therefore, we focus on the 1^{st} and 2^{nd} generation bioethanol in this paper.

- Tax Credit – The Volumetric Ethanol Excise Tax Credit (VEETC) was created by the America Job Act in 2004, to motivate blending more bioethanol with gasoline. The blenders gain 0.45 $\frac{\$}{\text{gal}}$ of bioethanol blended with gasoline (McPhail et al. 2011);

- Tariff – To encourage production and blending US bioethanol with gasoline, 0.54 $\frac{\$}{\text{gal}}$ tariff for blending foreign bioethanol with gasoline was considered (McPhail et al. 2011). It is notable that the tariff for blending US bioethanol with gasoline is quite important for shifting the ethanol production towards current critical issues, for example, diverting ethanol for production of sanitizers to prevent the spread of pandemic Coronavirus Disease (COVID-19) (Voegele 2020a);

- Blend Wall (BW) – The highest amount of bioethanol (e.g., 10%) blended with each gallon of gasoline to be used in all gasoline engine vehicles is called Blend Wall (BW) (Renewable Fuels Association 2015). Under the US Clean Air Act 1963 (CAA), all gasoline engine vehicles are allowed to use up to 10% bioethanol blend with gasoline (referred to as E10); however, Flex-Fuel Vehicles (FFVs) are permitted to use up to 85% bioethanol blend with gasoline. Certain intermediate blends, e.g. 15% bioethanol blended with gasoline (E15), can be produced under certain circumstances by waiving the CAA. The E15 can be used by vehicle models manufactured later than 2000. Currently, the BW is 10% and, in general, E10 is the only gasoline consumed in the US (Yacobucci 2010).

We approach the problem by developing an algorithm, a two-stage stochastic programming model, called Extended Lean Model (ELM) in this Part I. We include both the first and second generation bioethanol, their import and export, and all the existing infrastructures in the model. In an accompanying Part II, Ghahremanlou and Kubiak (2020b), we conduct a case study for the State of Nebraska using the ELM. The ELM permits us to solve 21,420 alternative policy scenarios to optimality for the purpose of the study, within a reasonable time, which is impossible to achieve with other models existing in the literature.

5.1.1 Literature Review

Thompson et al. (2009), Babcock (2012), Aguilar et al. (2015), and Whistance et al. (2016) analyze the US government policies from an economic point of view; they do not consider the supply chain point of view nor do they apply optimization models as in this paper. Thompson et al. (2009) use a supply and demand curve to demonstrate under what circumstances the RFS2 is not binding. Babcock (2012) reveals an increase in the US corn price can result from an increase in RFS2, TI, and TCL. Aguilar et al. (2015) conclude the US market is demanding fuel with a higher bioethanol amount. The study performed by Whistance et al. (2016) demonstrate the impact of RFS2 on agriculture and fuel markets.

The Conventional Crude Oil Supply Chain has been known to many people as a vital element of life for centuries, and many studies have been devoted to it, e.g., Smil (2017b), Wang et al. (2020), Yuan et al. (2019), Azadeh et al. (2017), Al-Qahtani et al. (2008), Al-Qahtani and Elkamel (2009), Carneiro et al. (2010), Ribas et al. (2010), Elkamel et al. (2008), and Guyonnet et al. (2009). The most recent reviews on CCOSC by Lima et al. (2016) and Sahebi et al. (2014b) highlight the study of new government incentives, real-life CCOSCs, and the development of efficient algorithms to solve real-life CCOSC optimization problems as the most promising avenues to explore for research.

The Bioethanol Supply Chain (BSC) has been extensively studied in the last two decades, e.g., Akbarian-Saravi et al. (2020), Giarola et al. (2012), Osmani and Zhang (2013), Gonela et al. (2015), Bairamzadeh et al. (2016), Ghaderi et al. (2018), Lozano-Moreno and Maréchal (2019), and Mele et al. (2011), since bioethanol may be a solution to global warming and energy dependency. The most recent reviews by Azevedo et al. (2019), Ghaderi et al. (2016) and Mafakheri and Nasiri (2014) emphasize the importance of government policies for the BSCs, and the need for models that incorporate them. Hence carrying out research on different countries and regions with different policies is an exciting research direction. It is worth mentioning that solving real-life BSC optimization models is quite challenging, therefore, the need for algorithms to overcome this challenge has been introduced as a very promising research avenue by Ghaderi et al. (2016), Ba et al. (2016), and Sharma et al. (2013).

Tong, You, and Rong (2014), Tong et al. (2013), Tong, Gleeson, Rong, and You (2014), Najmi et al. (2016), Andersen et al. (2013), Kazemzadeh and Hu (2015), Ghahremanlou and Kubiak (2020c), and Ghahremanlou and Kubiak (2020d) are the only papers focused on the sustainability of CCOSC that we are aware of. The first four papers have focused on drop-in biofuel, which is compatible with the existing infrastructures and a replacement for gasoline, although this is a solution for the future and is not currently available in the market (U.S. Department of Energy 2013). In this paper we study the SCOSC created by merging the BSC and the CCOSC, which has been studied by Andersen et al. (2013), Kazemzadeh and Hu (2015), Ghahremanlou and Kubiak (2020c), and Ghahremanlou and Kubiak (2020d). Andersen et al. (2013) developed a model to conduct research on the investment required to create the SCOSC in different regions of the US. Additionally, they develop a model to have a micro level study of bioethanol-gasoline blend (fuel) distribution within a state. Both of their models feature cost minimization and are deterministic, although uncertainty is inherent in the BSC which is a part of the SCOSC (Yue et al. 2014;

Meyer 2007; Awudu and Zhang 2012). Also, they do not consider the import and export of gasoline and bioethanol, which should be included to get closer to the real-life SCOSC. To our knowledge, Kazemzadeh and Hu (2015) is the only paper that includes government polices, RFS2 and TCL, in their two-stage stochastic model with annual expected profit maximization objective function. They solve nine optimization problems to find out the influence of RFS2 and TCL on the SCOSC. However, the paper does not include any information about how close their solutions are to optimality, nor do they incorporate bioethanol and gasoline import and export, and other government policies, i.e., TCI, TL, TI, and BW. The significance of efficient algorithms for solving the SCOSCs are re-emphasized in their research. Ghahremanlou and Kubiak (2020c), and Ghahremanlou and Kubiak (2020d) conduct a study for evaluating the impact of government policies on SCOSC in one of 23 states of the US without any bio-refinery in place, although 27 states already have infrastructure in place (Renewable Fuels Association 2010), which is the target of this study. Their SCOSC does not include: harvesting sites for first generation bioethanol, existing first and second generation bio-refineries, new first generation bio-refineries, first generation bioethanol exporters, and first generation bioethanol importers from other states and abroad.

To create the SCOSC for a state, by setting up some bio-refineries and blending sites to collaborate with existing infrastructures towards meeting the fuel demand within the state, we need to solve a Multi-echelon Location-Allocation (LA) problem (Shankar et al. 2013; Wang and Lee 2015; Cooper 1963; Ghahremanlou and Kubiak 2020c). The LA problem is observed in different fields, e.g., energy (Serrano-Hernandez et al. 2017; Liu et al. 2010; Ghahremanlou and Kubiak 2020c) and healthcare (Shariff et al. 2012; Syam and Côté 2012). The deterministic single-echelon LA problem is NP-hard due to its computational complexity resulting from many potential locations; therefore, it is impractical to solve such a problem to the optimality in a reasonable time frame by commercial optimization software like CPLEX and Gurobi. To overcome the complexity, available literature mainly offers heuristic algorithms, e.g., Bischoff and Dächert (2009); Murray and Church (1996), and decomposition methods, e.g., Kuenne and Soland (1972). However, finding optimal solution(s) for the deterministic single-echelon LA problem by employing heuristic approaches is not easy due to many near optimal solutions (Cooper 1964); also, there is no evidence that the decomposition algorithms work more efficiently than standard optimization software. Therefore, finding optimal solution(s) for the problem with many potential locations is out of reach currently. Consequently, to solve 21,420 two-stage stochastic multi-echelon location-allocation problems to optimality, efficiently, to investigate SCOSCs evolved by changing US government policies in the State of Nebraska with 93 counties, for the purpose of this study, is more complex. For instance, Chen and Fan (2012) apply the Progressive Hedging algorithm to solve a two-stage stochastic multi-echelon location-allocation problem with eight scenarios for the State of California and all its 58 counties; after 2 hours they only obtained a solution with 0.131% gap from optimality. This paper develops an algorithm called Extended Lean Model (ELM), which is an extension to the lean model (LM) proposed by Ghahremanlou and Kubiak (2020c) to deal with the computational complexity. The extension includes both the first and second generation bioethanol, their import and export, and the existing infrastructure which are not considered by the LM model.

5.1.2 Our Contributions

This paper and its companion part, Ghahremanlou and Kubiak (2020b), aim to propose an approach to examine and compare SCOSCs created in response to changing US government policies: Renewable Fuel Standard 2 (RFS2), Tax Credits for US and foreign bioethanol blended with gasoline (TCL and TCI respectively), Tariffs for US and foreign bioethanol blended with gasoline (TL and TI respectively), and Blend Wall (BW). To do this it is required to solve a two-stage stochastic multi-echelon location-allocation problem for each policy combination, referred to as an instance here, which is a six-tuple (RFS2, TCL, TCI, TL, TI, BW) of values for each RFS2, TCL, TCI, TL, TI, and BW. We have considered 21,420 instances in this study (details given in Section 3 of Ghahremanlou and Kubiak (2020b)). In this paper, Part I, we develop a two-stage stochastic multi-echelon location-allocation problem for our study, called Extended General Model (EGM), which is NP-hard like any other general model in the literature, then derive from it the ELM to overcome the NP-hardness and enable us to solve 21,420 instances to optimality in Part II, Ghahremanlou and Kubiak (2020b). The ELM aggregates all the flows in the SCOSC.

The rest of this paper is organized as follows: Section 5.2 describes the details of the problem; Section 5.3 explains the mathematical programming models developed in this study along with their relations in three subsections; Subsections 5.3.1 and 5.3.2 include the EGM and ELM for the given problem; Subsection 5.3.3 offers some key relations between both the models, which are proved in Appendix 5.5.3; we conclude and provide some further research directions in Section 5.4; all the notations and aggregated variables are left to the Appendix 5.5.1 and 5.5.2 respectively.

5.2 Problem Statement

This study deals with the problem of designing and planning an SCOSC for a state within the US, considering the government policies. The investors are led and motivated by policies to create the SCOSC. These policies are: Renewable Fuel Standard 2 (RFS2), Tax Credit for local bioethanol blended with gasoline (TCL), and Tax Credit for foreign bioethanol blended with gasoline (TCI); however, there are some control policies: Tariff for blending local bioethanol with gasoline (TL), Tariff for blending foreign bioethanol with gasoline (TI), and Blend Wall (BW). The objective of this SCOSC is to meet the demand for fuel (bioethanol-gasoline blend) while maximizing the expected profit and expected number of jobs created. Since the underlining reason for establishing and leading the SCOSC are the policies, we incorporate all them: RFS2, TCL, TCI, TI, TL, and BW, in the model, to evaluate their influence on the SCOSC.

Figure 5.1 displays the SCOSC, which includes abbreviations that are used throughout this paper and its accompanying part, thus we recommend the readers keep them in mind. The SCOSC consists of several main elements: harvesting sites, bio-refineries, blending sites (BLs), bioethanol exporters, bioethanol importers, gasoline providers, distribution centers (DCs). This figure demonstrates that all elements are made up of several main parts, except BLs and DCs. The main parts for each element are as follows:

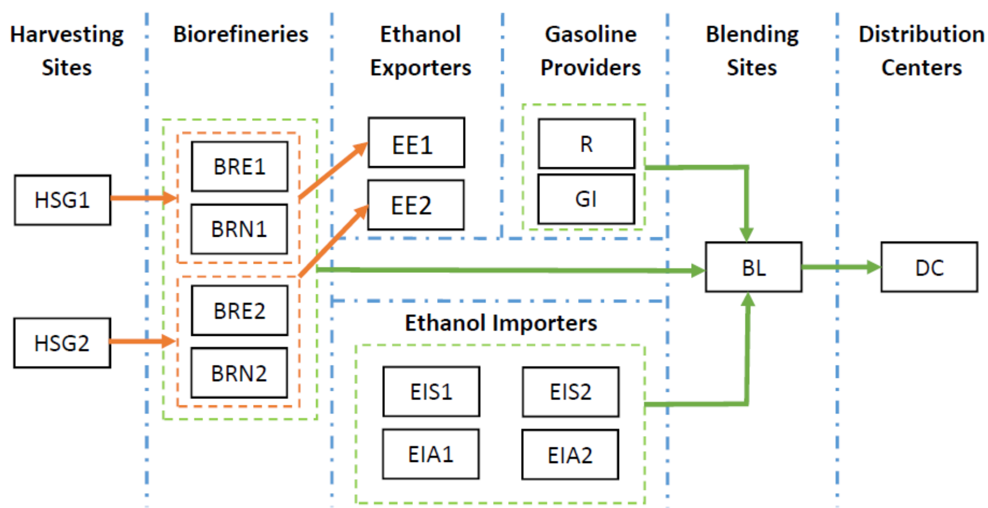


Figure 5.1: Sustainable Crude Oil Supply Chain Network

1. Harvesting sites: harvesting sites for 1^{st} generation bioethanol (HSG1s), harvesting sites for 2^{nd} generation bioethanol (HSG2s);

2. Bio-refineries: existing 1^{st} generation bio-refineries (BRE1s), new 1^{st} generation bio-refineries (BRN1s), existing 2^{nd} generation bio-refineries (BRE2s), new 2^{nd} generation bio-refineries (BRN2s);

3. Bioethanol exporters: 1^{st} generation bioethanol exporters (EE1s), 2^{nd} generation bioethanol exporters (EE2s);

4. Bioethanol importers: 1^{st} generation bioethanol importers from other states (EIS1s), 1^{st} generation bioethanol importers from abroad (EIA1s), 2^{nd} generation bioethanol importers from other states (EIS2s), 2^{nd} generation bioethanol importers from abroad (EIA2s);

5. Gasoline providers: refineries (Rs), gasoline importers (GIs).

There are no existing BLs in the model, since we require new BLs for blending and storing a higher amount of bioethanol with gasoline, e.g., 85% bioethanol blended with gasoline, due to the corrosive chemical property of bioethanol.

Strategic decisions, e.g., location selection, are very important in the SCOSC. We assume each county, $i \in N$, in the state has a HSG1, a HSG2, and a DC which are centrally located. The harvesting sites and DCs have their own amount of feedstock and fuel demand respectively. The HSG1s and HSG2s might not be fully or even partially used. In addition, the center of each county, $i \in N$, is considered as the potential location for setting up new facilities: a BRN1, a BRN2, or a BL. The budget for establishing the facilities is provided by a US government loan, which would be repaid within t years at an annual interest rate of Φ. Furthermore, the new facilities of the same type, e.g., BRN1s, have the same technology, but may have different capacities, hence different costs to set up. Moreover, we assume the existing facilities, BRE1s and BRE2s, are located in the center of their counties, which is consistent with our assumption for setting up new facilities. Sets $E1$ and $E2$ respectively denote the locations for BRE1s and BRE2s. A BRN1 is also allowed to be located in the same county as a BRE1; similarly a BRE2 might be in the same county as a BRN2. These would better clarify new investment opportunities, e.g., extending the BRE1s.

The tactical decisions in the SCOSC deal with the flows of materials: feedstock, bioethanol, gasoline, fuel. The feedstock is purchased from the suppliers. The L percent of feedstock is lost during harvesting and baling. Also, F percent of feedstock for producing 2^{nd} generation bioethanol is left on the land, at HSG2s, to maintain its fertility; the rest would be ready to ship to the corresponding bio-refineries. For example, the feedstock for producing 1^{st} generation bioethanol can be shipped to BRE1s and BRN1s. Each type of bio-refinery converts a specific portion of feedstock to bioethanol, which can be shipped to BLs and/or sold to bioethanol exporters. Selling to the exporters takes place at the bio-refineries locations. The bioethanol and gasoline are purchased from bioethanol importers and gasoline providers respectively, with the condition that they deliver them to blending sites locations. The bioethanol and gasoline are blended according to Blend Wall (BW) and shipped to distribution centers to meet the demand for fuel. Transportation from each harvesting site to the corresponding bio-refinery at any location, each bio-refinery to the blending site at any location, and each blending site to the distribution center at any location is permitted, and carried out by trucks. This incurs transportation distance-fixed and distance-variable costs.

The problem at hand encompasses two stages: in the first stage, locations of BRN1s, BRN2s, and BLs are determined, and in the second stage, flows of materials, feedstock, bioethanol, gasoline, fuel, are determined. The second stage decisions are influenced by a variety of uncertain factors. The uncertain factors in the expected profit maximization objective function are: the amount of feedstock in HSG1s and HSG2s, prices of feedstock at HSG1s and HSG2s, variable transportation costs for all flowing materials, 1^{st} and 2^{nd} generation bioethanol export prices, 1^{st} and 2^{nd} generation bioethanol import prices from other states, 1^{st} and 2^{nd} generation bioethanol import prices from abroad, gasoline price, fuel price, 1^{st} and 2^{nd} generation bioethanol RIN prices, and fuel demand. Additionally, there are some uncertain factors in expected number of jobs creation objective function, which are number of jobs created due to different activities: construction of BRN1s and BRN2s and BLs, transportation of feedstock for producing 1^{st} and 2^{nd} generation bioethanol, transportation of 1^{st} and 2^{nd} generation bioethanol, transportation of fuel, and conversion and blending operations. Therefore, we consider a two-stage stochastic programming model to meet the objective of this study.

We consider two objectives, the expected profit and expected number of jobs created, for evaluating the economic and social aspects of the SCOSC, respectively. The environmental aspect of the SCOSC will be analyzed by calculating the amount of bioethanol blended. Additionally, robust strategic decisions, against the policy change, are derived from the expected profit objective function. We maximize the expected profit annually, as the main objective function, while the secondary objective function is maximization of the expected number of jobs created in the state within the project lifetime of Q years. We assume that jobs are created only for: construction of new facilities (BRN1s, BRN2s and BLs), their operations (meaning conversion and blending), and transportation of materials (feedstock, bioethanol and fuel) in the SCOSC.

5.3 Formulation of Models

In this section two mathematical models are explained for the problem stated, see Section 5.2. The first one is the Extended General Model (EGM), which includes the details of facilities locations and flows. The second one is the Extended Lean Model (ELM), which is an aggregated model based on EGM.

5.3.1 Extended General Model (EGM)

We develop a two-stage stochastic programming model for the problem in this section. The design constraints are formulated in subsection 5.3.1.1, the flow constraints are given in subsection 5.3.1.2, and finally the objective functions are formulated in subsections 5.3.1.3, 5.3.1.4, and 5.3.1.5. We use the notations presented in Table 5.5.1.

5.3.1.1 Design Constraints

The design constraints are related to the locations and capacities of the new facilities: 1^{st} generation bio-refineries (BRN1s), 2^{nd} generation bio-refineries (BRN2s), and blending sites (BLs). The constraints (5.1), (5.2), and (5.3) guarantee that at most a BRN1, at most a BRN2, and at most a BL become established in each county of the state respectively. The $M1$, $M2$, and $M3$ are sets of capacity levels for BRN1s, BRN2s, and BLs respectively. Furthermore, the constraint (5.4) ensures that the total investment in the construction of BRN1s, BRN2s, and BLs in the state does not exceed the budget B.

$$\sum_{m\in M1} r_{mi}^{N1} \leq 1, \qquad \forall i \in N \tag{5.1}$$

$$\sum_{m\in M2} r_{mi}^{N2} \leq 1, \qquad \forall i \in N \tag{5.2}$$

$$\sum_{n\in M3} b_{nj} \leq 1, \qquad \forall j \in N \tag{5.3}$$

$$\sum_{m\in M1} C_m^{N1} \cdot \sum_{i\in N} r_{mi}^{N1} + \sum_{m\in M2} C_m^{N2} \cdot \sum_{i\in N} r_{mi}^{N2} + \sum_{n\in M3} W_n \cdot \sum_{j\in N} b_{nj} \leq B \tag{5.4}$$

5.3.1.2 Flow Constraints

Now we explain the flow constraints for scenario $s \in S$. Each county j has a known amount A^{C}_{js} of corn and A^{CS}_{js} of corn stover, of which a certain fraction L is lost due to harvesting. The constraint (5.5) shows that the collected corn $(1-L)\cdot A^{C}_{js}$ from county j can be shipped to BRE1s and BRN1s, $\sum\limits_{i\in E1} f^{E1}_{jis}$ and $\sum\limits_{i\in N} f^{N1}_{jis}$ respectively.

$$(1-L)\cdot A^{C}_{js} \geq \sum_{i\in E1} f^{E1}_{jis} + \sum_{i\in N} f^{N1}_{jis}, \qquad \forall j \in N \tag{5.5}$$

A portion F of corn stover is left in the land to maintain its fertility and the rest is harvested. The harvested corn stover from county j, left hand side of (5.6), can be transported to BRE2s and BRN2s, $\sum\limits_{i\in E2} f^{E2}_{jis}$ and $\sum\limits_{i\in N} f^{N2}_{jis}$ respectively.

$$(1-L)\cdot \left[(1-F)\cdot A^{CS}_{js}\right] \geq \sum_{i\in E2} f^{E2}_{jis} + \sum_{i\in N} f^{N2}_{jis}, \qquad \forall j \in N \tag{5.6}$$

The process of bioethanol production at each bio-refinery in the SCOSC is as follows:

- BRE1 – Each BRE1 at county $i \in E1$ converts V^{C} of corn it receives to bioethanol. The corn is shipped to each BRE1 from HSG1s at counties $j \in N$ in the state. The $\sum\limits_{j\in N} e^{E1}_{ijs}$ of produced bioethanol goes to all BLs located at counties $j \in N$ and the rest, o^{E1}_{is} bioethanol, is sold to EE1s

$$V^{C}\cdot \sum_{j\in N} f^{E1}_{jis} = \sum_{j\in N} e^{E1}_{ijs} + o^{E1}_{is}, \qquad \forall i \in E1. \tag{5.7}$$

- BRN1 – Each BRN1 set up at county $i \in N$ converts V^{C} of corn it receives to bioethanol. The corn is transported to each BRN1 from all harvesting sites for HSG1s at counties $j \in N$. The $\sum\limits_{j\in N} e^{N1}_{ijs}$ of produced bioethanol goes to all BLs established at counties $j \in N$ and the rest, o_{is}^{N1} bioethanol, is sold to EE1s

$$V^C \cdot \sum_{j \in N} f_{jis}^{N1} = \sum_{j \in N} e_{ijs}^{N1} + o_{is}^{N1}, \qquad \forall i \in N. \tag{5.8}$$

- BRE2 – Each BRE2 at county $i \in E2$ converts V^{CS} of corn stover it receives to bioethanol. The corn stover comes to each BRE2 from all harvesting sites for HSG2s at counties $j \in N$. The $\sum_{j \in N} e_{ijs}^{E2}$ of produced bioethanol goes to all BLs located at counties $j \in N$ and the rest, o_{is}^{E2} bioethanol, is sold to EE2s

$$V^{CS} \cdot \sum_{j \in N} f_{jis}^{E2} = \sum_{j \in N} e_{ijs}^{E2} + o_{is}^{E2}, \qquad \forall i \in E2. \tag{5.9}$$

- BRN2 – Each BRN2 established at county $i \in N$ converts V^{CS} of corn stover it receives to bioethanol. The corn stover is shipped to each BRN2 from all harvesting sites for HSG2s at counties $j \in N$. The $\sum_{j \in N} e_{ijs}^{N2}$ of produced bioethanol goes to all BLs set up at counties $j \in N$ and the rest, o_{is}^{N2} bioethanol, is sold to EE2s

$$V^{CS} \cdot \sum_{j \in N} f_{jis}^{N2} = \sum_{j \in N} e_{ijs}^{N2} + o_{is}^{N2}, \qquad \forall i \in N. \tag{5.10}$$

The constraint (5.11) shows the total amount of bioethanol received by each BL at county $j \in N$, left hand side of the constraint, must not exceed the BW, right hand side of the constraint. A BL at j receives $\sum_{i \in E1} e_{ijs}^{E1}$, $\sum_{i \in N} e_{ijs}^{N1}$, $\sum_{i \in E2} e_{ijs}^{E2}$, and $\sum_{i \in N} e_{ijs}^{N2}$ amount of bioethanol from BRE1s, BRN1s, BRE2s, and BRN2s. Also, it purchases h_{js}^{C} and k_{js}^{C} of the 1^{st} generation bioethanol and h_{js}^{CS} and k_{js}^{CS} of the 2^{nd} generation bioethanol from other states, and abroad, respectively. The amount g_{js} of gasoline is purchased to be blended with the bioethanol by a BL at j.

$$\left[\sum_{i\in E1} e^{E1}_{ijs} + \sum_{i\in N} e^{N1}_{ijs} + \sum_{i\in E2} e^{E2}_{ijs} + \sum_{i\in N} e^{N2}_{ijs} + h^{C}_{js} + k^{C}_{js} + h^{CS}_{js} + k^{CS}_{js}\right] \leq \alpha\cdot\left[\sum_{i\in E1} e^{E1}_{ijs} + \sum_{i\in N} e^{N1}_{ijs} + \sum_{i\in E2} e^{E2}_{ijs} + \sum_{i\in N} e^{N2}_{ijs} + h^{C}_{js} + k^{C}_{js} + h^{CS}_{js} + k^{CS}_{js} + g_{js}\right], \quad \forall j \in N \tag{5.11}$$

The constraints (5.12) and (5.13) ensures that the total amount $\sum_{j\in N} h^{C}_{js}$ and $\sum_{j\in N} h^{CS}_{js}$ of the 1^{st} and 2^{nd} generation bioethanol purchased from other states annually will not respectively exceed their E^{C} and E^{CS} total yearly production capacity.

$$\sum_{j\in N} h^{C}_{js} \leq E^{C} \tag{5.12}$$

$$\sum_{j\in N} h^{CS}_{js} \leq E^{CS} \tag{5.13}$$

The constraint (5.14) shows the flow-in and flow-out for each blending site in county j. The left hand side of the constraint includes bioethanol and gasoline flowing into a BL and the right hand side is the fuel flow-out.

$$\left[\sum_{i\in E1} e^{E1}_{ijs} + \sum_{i\in N} e^{N1}_{ijs} + \sum_{i\in E2} e^{E2}_{ijs} + \sum_{i\in N} e^{N2}_{ijs} + h^{C}_{js} + k^{C}_{js} + h^{CS}_{js} + k^{CS}_{js} + g_{js}\right] = \sum_{i\in N} x_{jis}, \quad \forall j \in N \tag{5.14}$$

The constraint (5.15) ensures that the distribution center in county i receives the amount of fuel required to meet the demand D_{is} at county $i \in N$.

$$\sum_{j\in N} x_{jis} = D_{is}, \quad \forall i \in N \tag{5.15}$$

The constraints (5.16) and (5.17) ensure that the amount $\sum_{j\in N} f_{jis}^{E1}$ of corn and $\sum_{j\in N} f_{jis}^{E2}$ of corn stover, received by a BRE1 and BRE2 located in $i \in E1$ and $i \in E2$ must not exceed their U_i^{E1} and U_i^{E2} capacities, respectively. Likewise, the constraints (5.18) and (5.19) guarantee the same for the newly built bio-refineries. Similarly, the constraint (5.20) ensures the flow-in for a BL located in county j does not exceed its capacity.

$$\sum_{j\in N} f_{jis}^{E1} \leq U_i^{E1}, \qquad \forall i \in E1 \tag{5.16}$$

$$\sum_{j\in N} f_{jis}^{E2} \leq U_i^{E2}, \qquad \forall i \in E2 \tag{5.17}$$

$$\sum_{j\in N} f_{jis}^{N1} \leq \sum_{m\in M1} U_m^{N1} \cdot r_{mi}^{N1}, \qquad \forall i \in N \tag{5.18}$$

$$\sum_{j\in N} f_{jis}^{N2} \leq \sum_{m\in M2} U_m^{N2} \cdot r_{mi}^{N2}, \qquad \forall i \in N \tag{5.19}$$

$$\left[\sum_{i\in E1} e_{ijs}^{E1} + \sum_{i\in N} e_{ijs}^{N1} + \sum_{i\in E2} e_{ijs}^{E2} + \sum_{i\in N} e_{ijs}^{N2} + h_{js}^{C} + k_{js}^{C} + h_{js}^{CS} + k_{js}^{CS} + g_{js}\right] \leq \sum_{n\in M3} H_n \cdot b_{nj}, \forall j \in N \tag{5.20}$$

5.3.1.3 The Mandate

Renewable Fuel Standard 2 (RFS2) places certain requirements on the obligated parties, US importers and refiners of gasoline. They must blend a minimum amount of renewable fuels, referred to as mandate, with their gasoline annually. The definitions (5.21) and (5.22) show the mandates for the 1^{st} and 2^{nd} generation bioethanol for the SCOSC considered in this chapter

$$M_s^C := \overline{R} \cdot \sum_{j\in N} g_{js}, \qquad \forall s \in S \tag{5.21}$$

$$M_s^{CS} := \beta \cdot \overline{\overline{R}} \cdot \sum_{j \in N} g_{js}, \qquad \forall s \in S \tag{5.22}$$

where $\overline{R}$ and $\overline{\overline{R}}$ are current renewable fuel standards for the 1^{st} and 2^{nd} generation bioethanol respectively. The 1^{st} generation bioethanol is completely developed and matured, therefore, we only need to consider the coefficient β for $\overline{\overline{R}}$ to capture the policy changes (Sharma et al. 2013; Ghahremanlou and Kubiak 2020c).

The investors must deliver their Renewable Identification Numbers, RINs, to meet the mandates. One gallon of bioethanol equals one RIN. The RINs are separated when bioethanol is blended with gasoline. The separated RINs are compared to the mandate; the comparison results in the following three possibilities: (1) RINs are enough to meet the mandate; (2) RINs are less than the mandate and the deficiency must be purchased; (3) RINs are more than the mandate and the extra ones are sold. Accordingly, RIN_s^C (for 1^{st} generation bioethanol) and RIN_s^{CS} (for 2^{nd} generation bioethanol), in equations (5.23) and (5.24), may be zero, negative (incurring cost) or positive (generating revenue).

$$RIN_s^C := \sum_{j \in N} \left[\sum_{i \in E1} e_{ijs}^{E1} + \sum_{i \in N} e_{ijs}^{N1} + h_{js}^C + k_{js}^C \right] - M_s^C, \qquad \forall s \in S \tag{5.23}$$

$$RIN_s^{CS} := \sum_{j \in N} \left[\sum_{i \in E2} e_{ijs}^{E2} + \sum_{i \in N} e_{ijs}^{N2} + h_{js}^{CS} + k_{js}^{CS} \right] - M_s^{CS}, \qquad \forall s \in S \tag{5.24}$$

5.3.1.4 Expected Profit Maximization Objective Function

We calculate the annual expected profit maximization objective function

$$G_1 = TR - TC \tag{5.25}$$

by deducting the total annual expected costs

$$TC = C^A + C^F + C^O + C^T + C^I + C^G \tag{5.26}$$

from the total annual expected revenues

$$TR = R^R + R^S + R^L + R^I + R^{EE}. \tag{5.27}$$

We explain the components of TC and TR below.

The price for a single 1^{st} generation bioethanol RIN at scenario $s \in S$, with probability ω_s, equals P_s^{RC}. Likewise, the price for a single 2^{nd} generation bioethanol RIN at scenario $s \in S$, with probability ω_s, equals P_s^{RCS}. Thus, we have

$$R^R = \sum_{s \in S} \left(P_s^{RC} \cdot RIN_s^C + P_s^{RCS} \cdot RIN_s^{CS} \right) \cdot \omega_s. \tag{5.28}$$

The fuel is sold at the market price P_s to generate expected revenue

$$R^S = \sum_{s \in S} P_s \cdot \omega_s \cdot \sum_{i \in N} D_{is}. \tag{5.29}$$

Observe that this expected revenue is variable independent.

The bioethanol produced inside the US blended with gasoline contributes to the expected revenue

$$R^L = \eta \cdot T \cdot \sum_{s \in S} \omega_s \cdot \sum_{j \in N} \left[\sum_{i \in E1} e_{ijs}^{E1} + \sum_{i \in N} e_{ijs}^{N1} + \sum_{i \in E2} e_{ijs}^{E2} + \sum_{i \in N} e_{ijs}^{N2} + h_{js}^{C} + h_{js}^{CS} \right] \tag{5.30}$$

through Tax Credit T dollar per gallon. The coefficient η accounts for the government's decisions to change the Tax Credit for US bioethanol, TCL. If $\eta > 0$, R^L is expected revenue obtained from TCL, however, if $\eta < 0$, R^L is expected cost incurred from a tariff on blending local bioethanol with gasoline, TL.

The imported bioethanol blended with gasoline contributes to the expected revenue

$$R^{I} = \theta \cdot \overline{T} \cdot \sum_{s \in S} \omega_s \cdot \sum_{j \in N} \left[k_{js}^{C} + k_{js}^{CS} \right] \tag{5.31}$$

through Tax Credit $\overline{T}$ dollar per gallon. The coefficient θ accounts for the government's decisions to change the Tax Credit for foreign bioethanol, TCI. If $\theta > 0$, R^I is expected revenue obtained from TCI, however, if $\theta < 0$, R^I is expected cost incurred from a tariff on blending foreign bioethanol with gasoline, TI.

Selling 1^{st} and 2^{nd} generation bioethanol to the exporters, EE1s and EE2s respectively, generates expected revenue, R^{EE}. The $\sum_{i \in E1} o_{is}^{E1}$ and $\sum_{i \in N} o_{is}^{N1}$, 1^{st} generation bioethanol sold respectively by BRE1s and BRN1s to EE1s, at the price of P_s^{EC} per gallon make up a portion of R^{EE}. Likewise, $\sum_{i \in E2} o_{is}^{E2}$ and $\sum_{i \in N} o_{is}^{N2}$, 2^{nd} generation bioethanol sold respectively by BRE2s and BRN2s to EE2s, at the price of P_s^{ECS} per gallon make up another portion of R^{EE}

$$R^{EE} = \sum_{s \in S} \left(P_s^{EC} \cdot \left[\sum_{i \in E1} o_{is}^{E1} + \sum_{i \in N} o_{is}^{N1} \right] + P_s^{ECS} \cdot \left[\sum_{i \in E2} o_{is}^{E2} + \sum_{i \in N} o_{is}^{N2} \right] \right) \cdot \omega_s. \tag{5.32}$$

The equation (5.33) shows the annual payment C^A for a loan to set up BRN1s, BRN2s and BLs. The loan has an interest rate Φ and a repay duration of t years.

$$C^{A} = \left[\frac{\Phi \cdot (1+\Phi)^t}{(1-\Phi)^t - 1} \right] \cdot \left[\sum_{m \in M1} C_m^{N1} \cdot \sum_{i \in N} r_{mi}^{N1} + \sum_{m \in M2} C_m^{N2} \cdot \sum_{i \in N} r_{mi}^{N2} + \sum_{n \in M3} W_n \cdot \sum_{j \in N} b_{nj} \right] \tag{5.33}$$

The expected cost associated with purchasing corn and corn stover to produce bioethanol, is calculated according to equation (5.34). The prices of corn and corn stover are respectively

P_s^C and P_s^{CS} in scenario $s \in S$, with probability ω_s.

$$C^F = \sum_{s\in S}\left(P_s^C \cdot \sum_{j\in N}\left[\sum_{i\in E1} f_{jis}^{E1} + \sum_{i\in N} f_{jis}^{N1}\right] + P_s^{CS} \cdot \sum_{j\in N}\left[\sum_{i\in E2} f_{jis}^{E2} + \sum_{i\in N} f_{jis}^{N2}\right]\right) \cdot \omega_s \quad (5.34)$$

The expected operation costs

$$C^O = C^{OC} + C^{OCS} + C^{OB}. \quad (5.35)$$

The C^O includes:

- The expected cost of conversion of corn to bioethanol C^{OC}: the cost associated with producing each unit of 1^{st} generation bioethanol equals C^{FEC}. The BRE1s and BRN1s respectively produce $\sum_{i\in E1}(\sum_{j\in N} e_{ijs}^{E1} + o_{is}^{E1})$ and $\sum_{i\in N}(\sum_{j\in N} e_{ijs}^{N1} + o_{is}^{N1})$ bioethanol, thus

$$C^{OC} = C^{FEC} \cdot \sum_{s\in S} \omega_s \cdot \left[\sum_{i\in E1}(\sum_{j\in N} e_{ijs}^{E1} + o_{is}^{E1}) + \sum_{i\in N}(\sum_{j\in N} e_{ijs}^{N1} + o_{is}^{N1})\right]. \quad (5.36)$$

- The expected cost of conversion of corn stover to bioethanol C^{OCS}: the cost associated with producing each unit of 2^{nd} generation bioethanol equals C^{FECS}. The BRE2s and BRN2s respectively produce $\sum_{i\in E2}(\sum_{j\in N} e_{ijs}^{E2} + o_{is}^{E2})$ and $\sum_{i\in N}(\sum_{j\in N} e_{ijs}^{N2} + o_{is}^{N2})$ bioethanol, thus

$$C^{OCS} = C^{FECS} \cdot \sum_{s\in S} \omega_s \cdot \left[\sum_{i\in E2}(\sum_{j\in N} e_{ijs}^{E2} + o_{is}^{E2}) + \sum_{i\in N}(\sum_{j\in N} e_{ijs}^{N2} + o_{is}^{N2})\right]. \quad (5.37)$$

- The expected cost of blending bioethanol with gasoline C^{OB}: the cost associated with producing each unit of fuel, by blending bioethanol and gasoline, equals C^B. The BLs produce $\sum_{i\in N} D_{is}$ fuel, thus

$$C^{OB} = C^{B} \cdot \sum_{s\in S} \omega_s \cdot \sum_{i\in N} D_{is}. \tag{5.38}$$

The total expected transportation cost

$$C^{T} = C^{TCE1} + C^{TCN1} + C^{TCSE2} + C^{TCSN2} + C^{TEE1} + C^{TEN1} + C^{TEE2} + C^{TEN2} + C^{TEG}. \tag{5.39}$$

Each component in equation (5.39), explained in equations (5.40)-(5.48), includes two main parts: (1) fixed expected transportation cost, which consists of one of C^{FTC}, C^{FTCS}, C^{FTE}, or C^{FTEG} that are fixed transportation costs per tonne; and (2) variable expected transportation cost, which consists of one of C_s^{VTC}, C_s^{VTCS}, C_s^{VTE}, or C_s^{VTEG} variable transportation costs per tonne times mile. The τ in the variable expected transportation cost is a tortuosity factor used to make the distance (d_{ji} and d_{ij}) close to reality.

Transported materials in the SCOSC are feedstock, bioethanol, and fuel. Thus, the expected transportation costs can be categorized into three classes:

1. feedstock

   - corn from HSG1s to BRE1s

$$C^{TCE1} = \sum_{s\in S} \omega_s \cdot \left(C^{FTC} \cdot \sum_{j\in N} \sum_{i\in E1} f_{jis}^{E1} + \tau \cdot C_s^{VTC} \cdot \sum_{j\in N} \sum_{i\in E1} f_{jis}^{E1} \cdot d_{ji} \right) \tag{5.40}$$

   - corn from HSG1s to BRN1s

$$C^{TCN1} = \sum_{s \in S} \omega_s \cdot \left(C^{FTC} \cdot \sum_{j \in N} \sum_{i \in N} f_{jis}^{N1} + \tau \cdot C_s^{VTC} \cdot \sum_{j \in N} \sum_{i \in N} f_{jis}^{N1} \cdot d_{ji} \right) \quad (5.41)$$

- corn stover from HSG2s to BRE2s

$$C^{TCSE2} = \sum_{s \in S} \omega_s \cdot \left(C^{FTCS} \cdot \sum_{j \in N} \sum_{i \in E2} f_{jis}^{E2} + \tau \cdot C_s^{VTCS} \cdot \sum_{j \in N} \sum_{i \in E2} f_{jis}^{E2} \cdot d_{ji} \right) \quad (5.42)$$

- corn stover from HSG2s to BRN2s

$$C^{TCSN2} = \sum_{s \in S} \omega_s \cdot \left(C^{FTCS} \cdot \sum_{j \in N} \sum_{i \in N} f_{jis}^{N2} + \tau \cdot C_s^{VTCS} \cdot \sum_{j \in N} \sum_{i \in N} f_{jis}^{N2} \cdot d_{ji} \right) \quad (5.43)$$

2. bioethanol

- from BRE1s to BLs

$$C^{TEE1} = \sum_{s \in S} \omega_s \cdot \left(C^{FTE} \cdot \sum_{j \in N} \sum_{i \in E1} e_{ijs}^{E1} + \tau \cdot C_s^{VTE} \cdot \sum_{j \in N} \sum_{i \in E1} e_{ijs}^{E1} \cdot d_{ij} \right) \quad (5.44)$$

- from BRN1s to BLs

$$C^{TEN1} = \sum_{s \in S} \omega_s \cdot \left(C^{FTE} \cdot \sum_{j \in N} \sum_{i \in N} e_{ijs}^{N1} + \tau \cdot C_s^{VTE} \cdot \sum_{j \in N} \sum_{i \in N} e_{ijs}^{N1} \cdot d_{ij} \right) \quad (5.45)$$

- from BRE2s to BLs

$$C^{TEE2} = \sum_{s \in S} \omega_s \cdot \left(C^{FTE} \cdot \sum_{j \in N} \sum_{i \in E2} e^{E2}_{ijs} + \tau \cdot C^{VTE}_s \cdot \sum_{j \in N} \sum_{i \in E2} e^{E2}_{ijs} \cdot d_{ij} \right) \quad (5.46)$$

- from BRN2s to BLs

$$C^{TEN2} = \sum_{s \in S} \omega_s \cdot \left(C^{FTE} \cdot \sum_{j \in N} \sum_{i \in N} e^{N2}_{ijs} + \tau \cdot C^{VTE}_s \cdot \sum_{j \in N} \sum_{i \in N} e^{N2}_{ijs} \cdot d_{ij} \right) \quad (5.47)$$

3. fuel from BLs to DCs

$$C^{TEG} = \sum_{s \in S} \omega_s \cdot \left(C^{FTEG} \cdot \sum_{j \in N} \sum_{i \in N} x_{jis} + \tau \cdot C^{VTEG}_s \cdot \sum_{j \in N} \sum_{i \in N} x_{jis} \cdot d_{ji} \right) \quad (5.48)$$

The expected cost of importing bioethanol

$$C^{I} = \sum_{s \in S} \omega_s \cdot \left(P^{IC}_s \cdot \sum_{j \in N} h^{C}_{js} + P^{FC}_s \cdot \sum_{j \in N} k^{C}_{js} + P^{ICS}_s \cdot \sum_{j \in N} h^{CS}_{js} + P^{FCS}_s \cdot \sum_{j \in N} k^{CS}_{js} \right) \quad (5.49)$$

is comprised of the expected cost of purchasing:

1. the $\sum_{j \in N} h^{C}_{js}$ of 1^{st} generation bioethanol from other states with unit cost of P^{IC}_s dollar per gallon;

2. the $\sum_{j \in N} k^{C}_{js}$ of 1^{st} generation bioethanol from other countries with unit cost of P^{FC}_s dollar per gallon;

3. the $\sum_{j \in N} h^{CS}_{js}$ of 2^{nd} generation bioethanol from other states with unit cost of P^{ICS}_s dollar per gallon;

4. the $\sum_{j \in N} k^{CS}_{js}$ of 2^{nd} generation bioethanol from other countries with unit cost of P^{FCS}_s

dollar per gallon.

The cost of purchasing $\sum_{j \in N} g_{js}$ petroleum gasoline to blend with bioethanol at BLs

$$C^G = \sum_{s \in S} P_s^G \cdot \omega_s \cdot \sum_{j \in N} g_{js} \tag{5.50}$$

where P_s^G is gasoline unit price per gallon in scenario s.

5.3.1.5 Expected Number of Jobs Created Objective Function

We measure the expected number of jobs created

$$G_2 = J^C + J^{TC} + J^{TCS} + J^{TE} + J^{TEG} + J^O \tag{5.51}$$

in the state during Q years life time of the project, due to new facilities, by plugging in the optimum solution of the expected profit model in G_2. The G_2 includes $J^C, J^{TC}, J^{TCS}, J^{TE}, J^{TEG}$ and J^O, which are categorized into three following divisions:

- *Construction* – The expected number J^C of jobs created by the construction of new facilities depends on the setup costs, shown in the brackets,

$$J^C = \sum_{s \in S} J_s^{Co} \cdot \omega_s \cdot \left[\sum_{m \in M1} C_m^{N1} \cdot \sum_{i \in N} r_{mi}^{N1} + \sum_{m \in M2} C_m^{N2} \cdot \sum_{i \in N} r_{mi}^{N2} + \sum_{n \in M3} W_n \cdot \sum_{j \in N} b_{nj} \right]. \tag{5.52}$$

- *Transportation* – The expected number of jobs created by transportation from and/or to new facilities fall in three main categories:

  1. Feedstock – This includes two main parts:

– The expected number J^{TC} of jobs created by transportation of corn from HSG1s to BRN1s

$$J^{TC} = Q \cdot \tau \cdot \sum_{s \in S} J_s^{TC} \cdot \omega_s \cdot \left[\sum_{j \in N} \sum_{i \in N} f_{jis}^{N1} \cdot d_{ji} \right]. \tag{5.53}$$

– The expected number J^{TCS} of jobs created by transportation of corn stover from HSG2s to BRN2s

$$J^{TCS} = Q \cdot \tau \cdot \sum_{s \in S} J_s^{TCS} \cdot \omega_s \cdot \left[\sum_{j \in N} \sum_{i \in N} f_{jis}^{N2} \cdot d_{ji} \right]. \tag{5.54}$$

2. Bioethanol – The expected number J^{TE} of jobs created by transportation of the bioethanol from BRN1s and BRN2s to BLs

$$J^{TE} = Q \cdot \tau \cdot \sum_{s \in S} J_s^{TE} \cdot \omega_s \cdot \left[\sum_{j \in N} \sum_{i \in N} e_{ijs}^{N1} \cdot d_{ij} + \sum_{j \in N} \sum_{i \in N} e_{ijs}^{N2} \cdot d_{ij} \right] \tag{5.55}$$

3. Fuel – The expected number J^{TEG} of jobs created by transportation of fuel from BLs to DCs

$$J^{TEG} = Q \cdot \tau \cdot \sum_{s \in S} J_s^{TEG} \cdot \omega_s \cdot \left[\sum_{j \in N} \sum_{i \in N} x_{jis} \cdot d_{ji} \right] \tag{5.56}$$

- *Operations* – The expected number J^{O} of jobs created by the operation,

$$J^{O} = Q \cdot \sum_{s \in S} \omega_s \cdot \left[J_s^{CE} \cdot \sum_{m \in M1} C_m^{N1} \cdot \sum_{i \in N} r_{mi}^{N1} + J_s^{CSE} \cdot \sum_{m \in M2} C_m^{N2} \cdot \sum_{i \in N} r_{mi}^{N2} + J_s^{B} \cdot \sum_{n \in M3} W_n \cdot \sum_{j \in N} b_{nj} \right] \tag{5.57}$$

depends on the setup costs. By operations we refer to:

– conversion of corn to 1^{st} generation bioethanol at BRN1s;

– conversion of corn stover to 2^{nd} generation bioethanol at BRN2s;

– blending bioethanol and gasoline at BLs.

For further explanations on the definition of operations, see Gebreslassie et al. (2012a)).

We observe that G_2 is policy independent, none of Renewable Fuel Standard (RFS2), Tax Credit (TCL and TCI), Tariff (TL and TI), and the Blend Wall (BW) appeared in it. Therefore, policy changes do not influence G_2. Additionally, by comparing the two objective functions, G_2 and G_1, we observe that they are in conflict; increasing the expected number of jobs created by increasing the construction of new facilities, presented by equation (5.52), reduces the expected profit by increasing the loan annual payment, denoted by equation (5.33).

5.3.2 Extended Lean Model (ELM)

The EGM falls in the category of a location-allocation problem, which is demonstrated to be an NP-hard problem, see Section 5.1.1. Therefore, solving it to optimality efficiently for a single instance may not be easy. In addition, in this study the task is harder, as we need to solve an optimization problem for each combination of policies: α, β, θ, and η (Ghahremanlou and Kubiak 2020c). This results in thousands of policy scenarios, optimization problems or instances, since to investigate and compare the SCOSCs evolved in response to changing government policies we consider several values to each parameter, α, β, θ, and η. This is the motivation behind creating an ELM, which captures only the important details from the policy making and investment point of view. In this trade-off between the details and computation time, the flow details might not be necessary and realistic, as the project is in the planning stage. Therefore, we develop an ELM by aggregating variables over the locations.

5.3.2.1 Constraints

By employing aggregated variables in Appendix 5.5.2, we reformulate the EGM with some simplifications.

$$\sum_{m \in M1} r_m^{N1} \leq |N| \tag{5.58}$$

$$\sum_{m \in M2} r_m^{N2} \leq |N| \tag{5.59}$$

$$\sum_{n \in M3} b_n \leq |N| \tag{5.60}$$

respectively guarantee the number of new 1^{st} generation bio-refineries (BRN1s), new 2^{nd} generation bio-refineries (BRN2s), and blending sites (BLs) do not exceed the number of counties $|N|$.

$$\sum_{m \in M1} C_m^{N1} \cdot r_m^{N1} + \sum_{m \in M2} C_m^{N2} \cdot r_m^{N2} + \sum_{n \in M3} W_n \cdot b_n \leq B \tag{5.61}$$

ensures that the total cost to set up r_m^{N1} of BRN1s with capacity level $m \in M1$, r_m^{N2} of BRN2s with capacity level $m \in M2$, and b_n of BLs with capacity level $n \in M3$ must not exceed the budget B.

$$(1 - L) \cdot A_s^C \geq f_s^{E1} + f_s^{N1}, \qquad \forall s \in S \tag{5.62}$$

ensures that the total shipment of corn f_s^{E1} from HSG1s to BRE1s and the total shipment of corn f_s^{N1} from HSG1 to BRN1s do not exceed the total amount of corn available in the state in scenario s, A_s^C, after factoring in the L corn loss.

$$(1-L)\cdot(1-F)\cdot A_s^{CS} \geq f_s^{E2} + f_s^{N2}, \qquad \forall s \in S \tag{5.63}$$

guarantees that the total shipment of corn stover f_s^{E2} from HSG2s to BRE2s and the total shipment of corn stover f_s^{N2} from HSG2 to BRN2 do not exceed the total amount of corn stover available in the state in scenario s, A_s^{CS}, after factoring in the L corn loss and the F sustainability factor.

The total amount $V^C \cdot f_s^{E1}$ of bioethanol produced by BRE1s in scenario s equals the amount e_s^{E1} of bioethanol shipped by BRE1s to BLs and/or the amount o_s^{E1} of bioethanol sold by BRE1s to 1^{st} generation bioethanol exporters (EE1s)

$$V^C \cdot f_s^{E1} = e_s^{E1} + o_s^{E1}, \qquad \forall s \in S. \tag{5.64}$$

The total amount $V^C \cdot f_s^{N1}$ of bioethanol produced by BRN1s in scenario s equals the amount e_s^{N1} of bioethanol shipped by BRN1s to BLs and/or the amount o_s^{N1} of bioethanol sold by BRN1s to EE1s

$$V^C \cdot f_s^{N1} = e_s^{N1} + o_s^{N1}, \qquad \forall s \in S. \tag{5.65}$$

The total amount $V^{CS} \cdot f_s^{E2}$ of bioethanol produced by BRE2s in scenario s equals the amount e_s^{E2} of bioethanol shipped by BRE2s to BLs and/or the amount o_s^{E2} of bioethanol sold by BRE2s to 2^{nd} generation bioethanol exporters (EE2s)

$$V^{CS} \cdot f_s^{E2} = e_s^{E2} + o_s^{E2}, \qquad \forall s \in S. \tag{5.66}$$

The total amount $V^{CS} \cdot f_s^{N2}$ of bioethanol produced by BRN2s in scenario s equals the amount e_s^{N2} of bioethanol shipped by BRN2s to BLs and/or the amount o_s^{N2} of bioethanol sold by BRN2s to EE2s

$$V^{CS} \cdot f_s^{N2} = e_s^{N2} + o_s^{N2}, \qquad \forall s \in S. \tag{5.67}$$

$$e_s^{E1} + e_s^{N1} + e_s^{E2} + e_s^{N2} + h_s^{C} + k_s^{C} + h_s^{CS} + k_s^{CS} \leq \alpha \cdot D_s, \qquad \forall s \in S \tag{5.68}$$

ensures that the total amount of bioethanol received by BLs be less than the Blend Wall, the fraction α of fuel demand D_s in the state, in scenario s. The BLs receive e_s^{E1} of bioethanol from BRE1, e_s^{N1} of bioethanol from BRN1, e_s^{E2} of bioethanol from BRE2, and e_s^{N2} of bioethanol from BRN2s. They also receive h_s^{C} of bioethanol from 1^{st} generation bioethanol importers from other states (EIS1s), k_s^{C} of bioethanol from 1^{st} generation bioethanol importers from abroad (EIA1s), h_s^{CS} of bioethanol from 2^{nd} generation bioethanol importers from other states (EIS2s), and k_s^{CS} of bioethanol from 2^{nd} generation bioethanol importers from abroad (EIA2s).

$$h_s^{C} \leq E^{C}, \qquad \forall s \in S \tag{5.69}$$

ensures the amount h_s^{C} of bioethanol purchased from EIS1s does not exceed the total E^{C} capacity of 1^{st} generation bioethanol produced by other states.

$$h_s^{CS} \leq E^{CS}, \qquad \forall s \in S \tag{5.70}$$

ensures the amount h_s^{CS} of bioethanol purchased from EIS2s does not exceed the total E^{CS} capacity of 2^{nd} generation bioethanol produced by other states.

$$f_s^{E1} \leq U^{E1}, \qquad \forall s \in S \tag{5.71}$$

ensures the total amount f_s^{E1} of corn flow into BRE1s does not exceed their U^{E1} capacity in scenario s.

$$f_s^{E2} \leq U^{E2}, \qquad \forall s \in S \tag{5.72}$$

ensures the total amount f_s^{E2} of corn stover flow into BRE2s does not exceed their U^{E2} capacity in scenario s.

$$f_s^{N1} \leq \sum_{m \in M1} U_m^{N1} \cdot r_m^{N1}, \qquad \forall s \in S \tag{5.73}$$

ensures the total amount f_s^{N1} of corn flow into BRN1s does not exceed their $\sum_{m \in M1} U_m^{N1} \cdot r_m^{N1}$ capacity in scenario s.

$$f_s^{N2} \leq \sum_{m \in M2} U_m^{N2} \cdot r_m^{N2}, \qquad \forall s \in S \tag{5.74}$$

ensures the total amount f_s^{N2} of corn stover flow into BRN2s does not exceed their $\sum_{m \in M2} U_m^{N2} \cdot r_m^{N2}$ capacity in scenario s.

$$D_s \leq \sum_{n \in M3} H_n \cdot b_n, \qquad \forall j \in N, \forall s \in S \tag{5.75}$$

guarantees the total demand D_s for the fuel does not exceed the capacity $\sum_{n \in M3} H_n \cdot b_n$ of BLs.

To convert the EGM to the ELM, in order to reduce the computation time, we categorize all the flows in the EGM into the two main categories:

1. the internal flow, which represents the flow between two different elements in the SCOSC located at the same county;

2. the external, which represents the flow between two different elements in the SCOSC not located at the same county;

This classification helps to obtain more accurate solutions for the ELM, meaning the solutions which could better approximate the solutions in the EGM.

$$f_s^{N1} = f_s^{N1I} + f_s^{N1E}, \qquad \forall s \in S \tag{5.76}$$

splits the corn flow f_s^{N1} between all HSG1s and BRN1s into internal flow f_s^{N1I} and external flow f_s^{N1E}.

$$f_s^{N2} = f_s^{N2I} + f_s^{N2E}, \qquad \forall s \in S \tag{5.77}$$

splits corn stover flow f_s^{N2} between all HSG2s and BRN2s into internal flow f_s^{N2I} and external flow f_s^{N2E}.

$$e_s^{N1} = e_s^{N1I} + e_s^{N1E}, \qquad \forall s \in S \tag{5.78}$$

splits the corn flow e_s^{N1} between all BRN1s and BLs into internal flow e_s^{N1I} and external flow, e_s^{N1E}.

$$e_s^{N2} = e_s^{N2I} + e_s^{N2E}, \qquad \forall s \in S \tag{5.79}$$

splits corn stover flow e_s^{N2} between all BRN2s and BLs into internal flow e_s^{N2I} and external flow, e_s^{N2E}.

The shipment of fuel demand D_s from BLs to DCs can be split into internal flow x_s^I and external flow x_s^E

$$D_s = x_s^I + x_s^E, \qquad \forall s \in S. \tag{5.80}$$

For the flow-in and flow-out of the existing facilities (BRE1s and BRE2s), we assume that each existing facility is located in the center of the county it is located in. This is in line with the assumption that potential locations for the new facilities are the centers of the counties. Therefore,

- the flow-in to BRE1s

$$f_s^{E1} = f_s^{E1I} + f_s^{E1E}, \qquad \forall s \in S \tag{5.81}$$

  splits the corn flow f_s^{E1} into internal flow f_s^{E1I} and external flow f_s^{E1E}.

- the flow-in to BRE2s

$$f_s^{E2} = f_s^{E2I} + f_s^{E2E}, \qquad \forall s \in S \tag{5.82}$$

  splits the corn stover flow f_s^{E2} into internal flow f_s^{E2I} and external flow f_s^{E2E}.

- the flow-out of BRE1s

$$e_s^{E1} = e_s^{E1I} + e_s^{E1E}, \qquad \forall s \in S \tag{5.83}$$

  splits the flow of bioethanol e_s^{E1} into internal e_s^{E1I} and external flow e_s^{E1E}.

- the flow-out of BRE2s

$$e_s^{E2} = e_s^{E2I} + e_s^{E2E}, \qquad \forall s \in S \tag{5.84}$$

  splits the flow of bioethanol e_s^{E2} into internal e_s^{E2I} and external flow e_s^{E2E}.

To obtain more accurate solutions from the ELM, which better represent their counterpart solutions in the EGM, in addition to splitting the flows into external and internal flows, we add constraints (5.85)-(5.103). These constraints also help toward creating interesting relations between the EGM and the ELM, see Section 5.3.3. For example, One of these relations proves that a solution of the ELM could be converted to a solution of the EGM. Note that constraints (5.85)-(5.103) are linear, as the right hand sides are constants; the reason being that first stage decisions, e.g., locations, are determined and then accordingly the amount of flows are decided.

Define $B^{N1}_{mjs} = \min\{A^{C}_{js} \cdot (1-L), U^{N1}_{m}\}$ for $m \in M1$, $j \in N$, and $s \in S$. Also, define $|M1| \cdot |N|$ binary variables S^{N1}_{mj} for $m \in M1$ and $j \in N$. We add the following constraints:

$$\sum_{j \in N} S^{N1}_{mj} = r^{N1}_{m}, \qquad \forall m \in M1 \tag{5.85}$$

$$\sum_{m \in M1} S^{N1}_{mj} \leq 1, \qquad \forall j \in N \tag{5.86}$$

and

$$f^{N1I}_{s} \leq \sum_{j \in N} \sum_{m \in M1} B^{N1}_{mjs} \cdot S^{N1}_{mj}, \qquad \forall s \in S. \tag{5.87}$$

Define $B^{N2}_{mjs} = \min\{A^{CS}_{js} \cdot (1-L) \cdot (1-F), U^{N2}_{m}\}$ for $m \in M2$, $j \in N$, and $s \in S$. Additionally, define $|M2| \cdot |N|$ binary variables S^{N2}_{mj} for $m \in M2$ and $j \in N$. We add the following constraints:

$$\sum_{j \in N} S^{N2}_{mj} = r^{N2}_{m}, \qquad \forall m \in M2 \tag{5.88}$$

$$\sum_{m \in M2} S^{N2}_{mj} \leq 1, \qquad \forall j \in N \tag{5.89}$$

and

$$f^{N2I}_{s} \leq \sum_{j \in N} \sum_{m \in M2} B^{N2}_{mjs} \cdot S^{N2}_{mj}, \qquad \forall s \in S. \tag{5.90}$$

Define $C_{njs} = \min\{D_{js}, H_{n}\}$ for $n \in M3$, $j \in N$, and $s \in S$. Furthermore, define $|M3| \cdot |N|$ binary variables T_{n1} for $n \in M3$ and $j \in N$. We add the following constraints:

$$\sum_{j \in N} T_{nj} = b_n, \qquad \forall n \in M3 \tag{5.91}$$

$$\sum_{n \in M3} T_{nj} \leq 1, \qquad \forall j \in N \tag{5.92}$$

and

$$x_s^I \leq \sum_{j \in N} \sum_{n \in M3} C_{njs} \cdot T_{nj}, \qquad \forall s \in S. \tag{5.93}$$

It is important to mention that constraints (5.87), (5.90) and (5.93) do not allow us to take advantage of the concavity property of bio-refineries and blending sites cost function; for more details see examples for Observation 11. Otherwise, one could say facilities with bigger capacities are preferred, meaning instead of two bio-refineries of capacity level one, one with capacity level 2 is preferred.

Define $E_{mn}^{N1} = \min\{V^C \cdot U_m^{N1}, \alpha \cdot H_n\}$ for $m \in M1$, and $n \in M3$. The following constraints limit the internal flow of bioethanol out of BRN1s:

$$e_s^{N1I} \leq \sum_{m \in M1} \sum_{n \in M3} \sum_{j \in N} E_{mn}^{N1} \cdot P_{mnj}^{N1}, \qquad \forall s \in S \tag{5.94}$$

$$\sum_{n \in M3} P_{mnj}^{N1} \leq S_{mj}^{N1}, \qquad \forall j \in N, \forall m \in M1 \tag{5.95}$$

and

$$\sum_{m \in M1} P_{mnj}^{N1} \leq T_{nj}, \qquad \forall j \in N, \forall n \in M3. \tag{5.96}$$

Observe that the two constraints (5.95) and (5.96) imply that for $P_{mnj}^{N1} = 1$ it is necessary, but not sufficient, that both a bio-refinery of size U_m^{N1} and blending site of size H_n be established in j. However, in an optimal solution, when $S_{mj}^{N1} = 1$ and $T_{nj} = 1$ then $P_{mnj}^{N1} = 1$, since e_s^{N1I} will be maximized and therefore P_{mnj}^{N1} has to reach its cap.

Define $E_{mn}^{N2} = \min\{V^{CS} \cdot U_m^{N2}, \alpha \cdot H_n\}$ for $m \in M2$, and $n \in M3$. The following constraints limit the internal flow of bioethanol out of BRN2s:

$$e_s^{N2I} \leq \sum_{m \in M2} \sum_{n \in M3} \sum_{j \in N} E_{mn}^{N2} \cdot P_{mnj}^{N2}, \qquad \forall s \in S \tag{5.97}$$

$$\sum_{n \in M3} P_{mnj}^{N2} \leq S_{mj}^{N2}, \qquad \forall j \in N, \forall m \in M2 \tag{5.98}$$

and

$$\sum_{m \in M2} P_{mnj}^{N2} \leq T_{nj}, \qquad \forall j \in N, \forall n \in M3. \tag{5.99}$$

Observe that the two constraints (5.98) and (5.99) imply that for $P_{mnj}^{N2} = 1$ it is necessary, but not sufficient, that both a bio-refinery of size U_m^{N2} and blending site of size H_n be established in j. However, in the optimal solution, when $S_{mj}^{N2} = 1$ and $T_{nj} = 1$ then $P_{mnj}^{N2} = 1$, since e_s^{N2I} will be maximized and therefore P_{mnj}^{N2} has to reach its cap.

$$f_s^{E1I} \leq \sum_{i \in E1} \min\{U_i^{E1}, (1-L) \cdot A_{is}^{C}\} \qquad \forall s \in S \tag{5.100}$$

and

$$f_s^{E2I} \leq \sum_{i \in E2} \min\{U_i^{E2}, (1-L) \cdot (1-F) \cdot A_{is}^{CS}\} \qquad \forall s \in S \tag{5.101}$$

create upper bounds for f_s^{E1I} and f_s^{E2I}.

Define $A_{ni}^{E1} = \min\{V^{C} \cdot U_i^{E1}, \alpha \cdot H_n\}$ for $i \in E1$, and $n \in M3$. The constraint (5.102) creates an upper bound for e_s^{E1I}. Let's note that T_{ni} for $n \in M3$ and $i \in E1$ are binary variables which make up a part of the binary variables introduced in constraints (5.91)-(5.93) initially.

$$e_s^{E1I} \leq \sum_{i \in E1} \sum_{n \in M3} A_{ni}^{E1} \cdot T_{ni}, \qquad \forall s \in S \tag{5.102}$$

Define $A_{ni}^{E2} = \min\{V^{CS} \cdot U_i^{E2}, \alpha \cdot H_n\}$ for $i \in E2$, and $n \in M3$. Constraint (5.103) creates upper bound for e_s^{E2I}. Let's note that T_{ni} for $n \in M3$ and $i \in E2$ are binary variables which make up a part of the binary variables introduced in constraints (5.91)-(5.93) initially.

$$e_s^{E2I} \leq \sum_{i \in E2} \sum_{n \in M3} A_{ni}^{E2} \cdot T_{ni}, \qquad \forall s \in S \tag{5.103}$$

Finally, we define the mandate

$$M_s^C := \overline{R} \cdot \left[D_s - (e_s^{E1} + e_s^{N1} + e_s^{E2} + e_s^{N2} + h_s^C + k_s^C + h_s^{CS} + k_s^{CS}) \right], \qquad \forall s \in S \tag{5.104}$$

for 1st generation bioethanol, and the mandate

$$M_s^{CS} := \beta \cdot \overline{\overline{R}} \cdot \left[D_s - (e_s^{E1} + e_s^{N1} + e_s^{E2} + e_s^{N2} + h_s^C + k_s^C + h_s^{CS} + k_s^{CS}) \right], \qquad \forall s \in S \tag{5.105}$$

for 2nd generation bioethanol. Similarly, the number of RINs

$$RIN_s^C := (e_s^{E1} + e_s^{N1} + h_s^C + k_s^C) - M_s^C, \qquad \forall s \in S \tag{5.106}$$

for 1st generation bioethanol, and the number of RINs

$$RIN_s^{CS} := (e_s^{E2} + e_s^{N2} + h_s^{CS} + k_s^{CS}) - M_s^{CS}, \qquad \forall s \in S \tag{5.107}$$

for 2nd generation bioethanol are defined.

5.3.2.2 ELM Objective Functions

The following expected revenue, expected cost, and expected number of jobs created are components of the ELM objective functions, defined in (5.108)-(5.140), exactly mirror those of the EGM objective functions, defined in (5.28)-(5.51). The former are essentially obtained from the latter by replacing the variables of the latter by their aggregations defined in Appendix 5.5.2.

$$R^R = \sum_{s \in S} \omega \cdot \left(P_s^{RC} \cdot RIN_s^C + P_s^{RCS} \cdot RIN_s^{CS} \right) \tag{5.108}$$

$$R^S = \sum_{s \in S} P_s \cdot \omega_s \cdot D_s \tag{5.109}$$

$$R^L = \eta \cdot T \cdot \sum_{s \in S} \omega_s \cdot (e_s^{E1} + e_s^{N1} + e_s^{E2} + e_s^{N2} + h_s^C + h_s^{CS}) \tag{5.110}$$

$$R^I = \theta \cdot \overline{T} \cdot \sum_{s \in S} \omega_s \cdot (k_s^C + k_s^{CS}) \tag{5.111}$$

$$R^{EE} = \sum_{s \in S} \omega_s \cdot \left[P_s^{EC} \cdot (o_s^{E1} + o_s^{N1}) + P_s^{ECS} \cdot (o_s^{E2} + o_s^{N2}) \right] \tag{5.112}$$

$$C^A = \left[\frac{\Phi \cdot (1+\Phi)^t}{(1-\Phi)^t - 1} \right] \cdot \left[\sum_{m \in M1} C_m^{N1} \cdot r_m^{N1} + \sum_{m \in M2} C_m^{N2} \cdot r_m^{N2} + \sum_{n \in M3} W_n \cdot b_n \right] \tag{5.113}$$

$$C^F = \sum_{s \in S} \omega_s \cdot \left[P_s^C \cdot (f_s^{E1} + f_s^{N1}) + P_s^{CS} \cdot (f_s^{E2} + f_s^{N2}) \right] \tag{5.114}$$

$$C^O = C^{OC} + C^{OCS} + C^{OB} \tag{5.115}$$

$$C^{OC} = C^{FEC} \cdot \sum_{s \in S} \omega_s \cdot (e_s^{E1} + o_s^{E1} + e_s^{N1} + o_s^{N1}) \tag{5.116}$$

$$C^{OCS} = C^{FECS} \cdot \sum_{s \in S} \omega_s \cdot (e_s^{E2} + o_s^{E2} + e_s^{N2} + o_s^{N2}) \tag{5.117}$$

$$C^{OB} = C^{B} \cdot \sum_{s \in S} \omega_s \cdot D_s \tag{5.118}$$

$$C^{T} = C^{TCE1} + C^{TCN1} + C^{TCSE2} + C^{TCSN2} + C^{TEE1} + C^{TEN1} + C^{TEE2} + C^{TEN2} + C^{TEG} \tag{5.119}$$

$$C^{TCE1} = \sum_{s \in S} \omega_s \cdot \left(C^{FTC} \cdot f_s^{E1} + \overline{d}^{E1} \cdot \tau \cdot C_s^{VTC} \cdot f_s^{E1E} \right) \tag{5.120}$$

$$C^{TCN1} = \sum_{s \in S} \omega_s \cdot \left(C^{FTC} \cdot f_s^{N1} + \overline{d} \cdot \tau \cdot C_s^{VTC} \cdot f_s^{N1E} \right) \tag{5.121}$$

$$C^{TCSE2} = \sum_{s \in S} \omega_s \cdot \left(C^{FTCS} \cdot f_s^{E2} + \overline{d}^{E2} \cdot \tau \cdot C_s^{VTCS} \cdot f_s^{E2E} \right) \tag{5.122}$$

$$C^{TCSN2} = \sum_{s \in S} \omega_s \cdot \left(C^{FTCS} \cdot f_s^{N2} + \overline{d} \cdot \tau \cdot C_s^{VTCS} \cdot f_s^{N2E} \right) \tag{5.123}$$

$$C^{TEE1} = \sum_{s \in S} \omega_s \cdot \left(C^{FTE} \cdot e_s^{E1} + \overline{d}^{E1} \cdot \tau \cdot C_s^{VTE} \cdot e_s^{E1E} \right) \tag{5.124}$$

$$C^{TEN1} = \sum_{s \in S} \omega_s \cdot \left(C^{FTE} \cdot e_s^{N1} + \overline{d} \cdot \tau \cdot C_s^{VTE} \cdot e_s^{N1E} \right) \tag{5.125}$$

$$C^{TEE2} = \sum_{s \in S} \omega_s \cdot \left(C^{FTE} \cdot e_s^{E2} + \overline{d}^{E2} \cdot \tau \cdot C_s^{VTE} \cdot e_s^{E2E} \right) \tag{5.126}$$

$$C^{TEN2} = \sum_{s \in S} \omega_s \cdot \left(C^{FTE} \cdot e_s^{N2} + \overline{d} \cdot \tau \cdot C_s^{VTE} \cdot e_s^{N2E}\right) \tag{5.127}$$

$$C^{TEG} = \sum_{s \in S} \omega_s \cdot \left(C^{FTEG} \cdot D_s + \overline{d} \cdot \tau \cdot C_s^{VTEG} \cdot x_s^{E}\right) \tag{5.128}$$

$$C^{I} = \sum_{s \in S} \omega_s \cdot \left(P_s^{IC} \cdot h_s^{C} + P_s^{FC} \cdot k_s^{C} + P_s^{ICS} \cdot h_s^{CS} + P_s^{FCS} \cdot k_s^{CS}\right) \tag{5.129}$$

$$C^{G} = \sum_{s \in S} P_s^{G} \cdot \omega_s \cdot \left[D_s - (e_s^{E1} + e_s^{N1} + e_s^{E2} + e_s^{N2} + h_s^{C} + k_s^{C} + h_s^{CS} + k_s^{CS})\right] \tag{5.130}$$

$$TR = R^{R} + R^{S} + R^{L} + R^{I} + R^{EE} \tag{5.131}$$

$$TC = C^{A} + C^{F} + C^{O} + C^{T} + C^{I} + C^{G} \tag{5.132}$$

$$L_1 = TR - TC \tag{5.133}$$

$$J^{C} = \sum_{s \in S} J_s^{Co} \cdot \omega_s \cdot \left[\sum_{m \in M1} C_m^{N1} \cdot r_m^{N1} + \sum_{m \in M2} C_m^{N2} \cdot r_m^{N2} + \sum_{n \in M3} W_n \cdot b_n\right] \tag{5.134}$$

$$J^{TC} = Q \cdot \tau \cdot \overline{d} \cdot \sum_{s \in S} J_s^{TC} \cdot \omega_s \cdot f_s^{N1E} \tag{5.135}$$

$$J^{TCS} = Q \cdot \tau \cdot \overline{d} \cdot \sum_{s \in S} J_s^{TCS} \cdot \omega_s \cdot f_s^{N2E} \tag{5.136}$$

$$J^{TE} = Q \cdot \tau \cdot \overline{d} \cdot \sum_{s \in S} J_s^{TE} \cdot \omega_s \cdot \left[e_s^{N1E} + e_s^{N2E}\right] \tag{5.137}$$

$$J^{TEG} = Q \cdot \tau \cdot \overline{d} \cdot \sum_{s \in S} J_s^{TEG} \cdot \omega_s \cdot x_s^E \tag{5.138}$$

$$J^O = Q \cdot \sum_{s \in S} \omega_s \cdot \left[J_s^{CE} \cdot \sum_{m \in M1} C_m^{N1} \cdot r_m^{N1} + J_s^{CSE} \cdot \sum_{m \in M2} C_m^{N2} \cdot r_m^{N2} + J_s^B \cdot \sum_{n \in M3} W_n \cdot b_n \right] \tag{5.139}$$

$$L_2 = J^C + J^{TC} + J^{TCS} + J^{TE} + J^{TEG} + J^O \tag{5.140}$$

Observe that the C^{TCE1}, C^{TCN1}, C^{TCSE2}, C^{TCSN2}, C^{TEE1}, C^{TEN1}, C^{TEE2}, C^{TEN2}, and C^{TEG} of objective function L_1, and J^{TC}, J^{TCS}, J^{TE}, and J^{TEG} of the objective function L_2 include $\overline{d}^{E1}$, $\overline{d}$, or $\overline{d}^{E2}$, which are used as the approximation of the distances between counties. Each distance approximation, $\overline{d}^{E1}$, $\overline{d}$, or $\overline{d}^{E2}$, takes on minimum or maximum distance as follows:

- $\bar{d}$ equals to $\delta = \min_{i \neq j} d_{ij} > 0, \forall i, j \in N$ or $\Delta = \max_{i \neq j} d_{ij} > 0, \forall i, j \in N$;
- $\bar{d}^{E1}$ equals to $\gamma = \min_{i \neq j} d_{ij} > 0, \forall i \in E1, \forall j \in N$ or $\Gamma = \max_{i \neq j} d_{ij} > 0, \forall i \in E1, \forall j \in N$;
- $\bar{d}^{E2}$ equals to $\lambda = \min_{i \neq j} d_{ij} > 0, \forall i \in E2, \forall j \in N$ or $\Lambda = \max_{i \neq j} d_{ij} > 0, \forall i \in E2, \forall j \in N$.

The optimal solution for L_1 where $\bar{d}$, $\bar{d}^{E1}$, and $\bar{d}^{E2}$ are approximated with minimum distances, δ, γ, and λ respectively, is $X_{\min}$. The $X_{\max}$ is the optimal solution for L_1 where $\bar{d}$, $\bar{d}^{E1}$, and $\bar{d}^{E2}$ are approximated with maximum distances Δ, Γ, and Λ respectively. From this point onward, $X_{\min}$ and $X_{\max}$ are called the best case and the worst case respectively.

5.3.3 Relationship Between EGM and ELM

In this Section we show the relationships between EGM and ELM.

Observation 6 *(Aggregation). Each feasible solution* $Y = (r^{N1}_{mi}, r^{N2}_{mi}, b_{nj}, f^{E1}_{jis}, f^{N1}_{jis}, f^{E2}_{jis}, f^{N2}_{jis}, e^{E1}_{ijs}, o^{E1}_{is}, e^{N1}_{ijs}, o^{N1}_{is}, e^{E2}_{ijs}, o^{E2}_{is}, e^{N2}_{ijs}, o^{N2}_{is}, h^{C}_{js}, k^{C}_{js}, h^{CS}_{js}, k^{CS}_{js}, g_{js}, x_{jis})$ *for the EGM, can be converted into a feasible solution* $X = (r^{N1}_{m}, r^{N2}_{m}, b_n, f^{E1}_s, f^{E1I}_s, f^{E1E}_s, f^{N1}_s, f^{N1I}_s, f^{N1E}_s, f^{E2}_s, f^{E2I}_s, f^{E2E}_s, f^{N2}_s, f^{N2I}_s, f^{N2E}_s, e^{E1}_s, e^{E1I}_s, e^{E1E}_s, o^{E1}_s, e^{N1}_s, e^{N1I}_s, e^{N1E}_s, o^{N1}_s, e^{E2}_s, e^{E2I}_s, e^{E2E}_s, o^{E2}_s, e^{N2}_s, e^{N2I}_s, e^{N2E}_s, o^{N2}_s, h^C_s, k^C_s, h^{CS}_s, k^{CS}_s, x_s)$ *for the ELM using the equations in Appendix 5.5.2.*

Observation 7 *(Disaggregation) Each optimal solution* $X = (r^{N1}_{m}, r^{N2}_{m}, b_n, f^{E1}_s, f^{E1I}_s, f^{E1E}_s, f^{N1}_s, f^{N1I}_s, f^{N1E}_s, f^{E2}_s, f^{E2I}_s, f^{E2E}_s, f^{N2}_s, f^{N2I}_s, f^{N2E}_s, e^{E1}_s, e^{E1I}_s, e^{E1E}_s, o^{E1}_s, e^{N1}_s, e^{N1I}_s, e^{N1E}_s, o^{N1}_s, e^{E2}_s, e^{E2I}_s, e^{E2E}_s, o^{E2}_s, e^{N2}_s, e^{N2I}_s, e^{N2E}_s, o^{N2}_s, h^C_s, k^C_s, h^{CS}_s, k^{CS}_s, x_s)$ *for the ELM, can be converted into a feasible solution* $Y = (r^{N1}_{mi}, r^{N2}_{mi}, b_{nj}, f^{E1}_{jis}, f^{N1}_{jis}, f^{E2}_{jis}, f^{N2}_{jis}, e^{E1}_{ijs}, o^{E1}_{is}, e^{N1}_{ijs}, o^{N1}_{is}, e^{E2}_{ijs}, o^{E2}_{is}, e^{N2}_{ijs}, o^{N2}_{is}, h^{C}_{js}, k^{C}_{js}, h^{CS}_{js}, k^{CS}_{js}, g_{js}, x_{jis})$ *for the EGM. The conversion is not unique.*

Observation 8 *For any* α, β, η *and* θ, *let* $X_{\min}$ *be an optimal solution to the ELM with* $\bar{d} = \delta$, $\bar{d}^{E1} = \gamma$, *and* $\bar{d}^{E2} = \lambda$. *Furthermore, let* $X_{\max}$ *be an optimal solution to the ELM with* $\bar{d} = \Delta$, $\bar{d}^{E1} = \Gamma$, *and* $\bar{d}^{E2} = \Lambda$. *Then,* $L_1(X_{\min}) \geq G_1(Y) \geq L_1(X_{\max})$ *for an optimal solution* Y *to* G_1 *of the EGM.*

Observation 9 *For any* α, β, η *and* θ, *let* $Z_{\min}$ *be an optimal solution to* L_2 *of the ELM with* $\bar{d} = \delta$. *Furthermore, let* $Z_{\max}$ *be an optimal solution to* L_2 *of the ELM with* $\bar{d} = \Delta$. *Then,* $L_2(Z_{\min}) \leq G_2(V) \leq L_2(Z_{\max})$ *for an optimal solution* V *to* G_2 *of the EGM.*

Let us define:

- $L_1^{\Delta,\Gamma,\Lambda}$ to be the ELM with objective function L_1 where $\bar{d} = \Delta$, $\bar{d}^{E1} = \Gamma$, and $\bar{d}^{E2} = \Lambda$;
- $L_1^{\delta,\gamma,\lambda}$ to be the ELM with objective function L_1 where $\bar{d} = \delta$, $\bar{d}^{E1} = \gamma$, and $\bar{d}^{E2} = \lambda$;
- L_2^{Δ} to be the ELM with objective function L_2 where $\bar{d} = \Delta$;
- L_2^{δ} to be the ELM with objective function L_2 where $\bar{d} = \delta$.

Then, we have Observation 10.

Observation 10 *For any α, β, η and θ, let Y_{min} and Y_{max} be optimal solutions to the ELM with the objective $L_1^{\Delta,\Gamma,\Lambda} + L_2^{\delta}$ and $L_1^{\delta,\gamma,\lambda} + L_2^{\Delta}$ respectively, then $L_1^{\Delta,\Gamma,\Lambda}(Y_{\min}) + L_2^{\delta}(Y_{\min}) \leq G_1(Y) + G_2(Y) \leq L_1^{\delta,\gamma,\lambda}(Y_{\max}) + L_2^{\Delta}(Y_{\max})$ for an optimal solution Y to $G_1 + G_2$ of the EGM.*

Observation 11 *Bio-refineries and blending sites with bigger capacities are not necessarily preferred.*

5.4 Conclusions and Further Research

We proposed an approach to studying Sustainable Crude Oil Supply Chains (SCOSCs) evolved in response to changing US government policies: Renewable Fuel Standard 2 (RFS2), Tax Credits for US and foreign bioethanol blended with gasoline (TCL and TCI respectively), Tariffs for US and foreign bioethanol blended with gasoline (TL and TI respectively), and Blend Wall (BW). We developed the Extended General Model (EGM) for the design of the SCOSC. The EGM is a two-stage stochastic multi-echelon location-allocation problem. The model includes both the first and second generation bioethanol, their import and export, and all the existing infrastructures. The model's computational complexity, which is inherent in the Location-Allocation problem, makes the model practically infeasible to solve in a reasonable time, even for a single policy scenario. We therefore developed an algorithm called the Extended Lean Model (ELM), based on the EGM, in order to overcome the EGM's computational complexity in computational experiments. The ELM permits us to solve 21,420 instances (policy scenarios) to optimality, within a reasonable time, in computational experiments reported in the accompanying Part II, Ghahremanlou and Kubiak (2020b), which makes the study feasible. The computational speed of the ELM results from the macro level view on the flows in the SCOSC. The ELM and aggregation at its core seem promising research avenues. Yet another research direction is the development of efficient algorithms for the EGM that use the ELM solutions to speed up the search for an optimal solution for EGM.

The EGM and ELM have two objective functions, with the primary one being the annual expected profit. The solution of the primary objective is then employed to measure the secondary objective function, the number of expected jobs within the life-time of the project. Other approaches to solving multi-objective optimization problems like Pareto Frontier, see Marler and Arora (2004) may provide further new insights in the SCOSCs analysis using the proposed approach.

5.5 Appendix

5.5.1 Notations

Sets

$E1$	set of locations for existing 1^{st} generation bio-refineries
$E2$	set of locations for existing 2^{nd} generation bio-refineries
$M1$	set of capacity levels for 1^{st} generation bio-refineries
$M2$	set of capacity levels for 2^{nd} generation bio-refineries
$M3$	set of capacity levels for blending sites
N	set of counties

S	set of scenarios

Indices

i, j	county index, $i, j \in N, E1, E2$
m	capacity level of bio-refineries $m \in \{1,2,3\}, M1, M2$
n	capacity level of blending sites $n \in \{1,2,3,4,5,6\}, M3$
s	scenario index, $s \in S$

Decision variables

Continuous non-negative variables for scenario $s \in S$

o_{is}^{E1}	amount of bioethanol sold to exporter from an existing 1^{st} generation bio-refinery in location $i \in E1$ (gal)
o_{is}^{N1}	amount of bioethanol sold to exporter from a new 1^{st} generation bio-refinery in county $i \in N$ (gal)
o_{is}^{E2}	amount of bioethanol sold to exporter from an existing 2^{nd} generation bio-refinery in location $i \in E2$ (gal)
o_{is}^{N2}	amount of bioethanol sold to exporter from a new 1^{st} generation bio-refinery in county $i \in N$ (gal)
e_{ijs}^{E1}	amount of bioethanol shipped from an existing 1^{st} generation bio-refinery in location $i \in E1$ to blending site in county $j \in N$ (gal)
e_{ijs}^{N1}	amount of bioethanol shipped from a new 1^{st} generation bio-refinery in county $i \in N$ to blending site in county $j \in N$ (gal)
e_{ijs}^{E2}	amount of bioethanol shipped from an existing 2^{nd} generation bio-refinery in location $i \in E2$ to blending site in county $j \in N$ (gal)
e_{ijs}^{N2}	amount of bioethanol shipped from a new 2^{nd} generation bio-refinery in county $i \in N$ to blending site in county $j \in N$ (gal)

f^{E1}_{jis} amount of corn shipped from harvesting site in county $j \in N$ to existing 1^{st} generation bio-refinery in location $i \in E1$ (MT)

f^{N1}_{jis} amount of corn shipped from harvesting site in county $j \in N$ to new 1^{st} generation bio-refinery in county $i \in N$ (MT)

f^{E2}_{jis} amount of corn stover shipped from harvesting site in county $j \in N$ to existing 2^{nd} generation bio-refinery in location $i \in E2$ (MT)

f^{N2}_{jis} amount of corn stover shipped from harvesting site in county $j \in N$ to new 2^{nd} generation bio-refinery in county $i \in N$ (MT)

g_{js} amount of gasoline (from crude oil) purchased for blending with bioethanol in blending site in county $j \in N$ (gal)

h^{C}_{js} amount of corn based bioethanol purchased from other states for blending with gasoline in blending site in county $j \in N$ (gal)

h^{CS}_{js} amount of corn stover based bioethanol purchased from other states for blending with gasoline in blending site in county $j \in N$ (gal)

k^{C}_{js} amount of corn based bioethanol purchased from other countries for blending with gasoline in blending site in county $j \in N$ (gal)

k^{CS}_{js} amount of corn stover based bioethanol purchased from other countries for blending with gasoline in blending site in county $j \in N$ (gal)

x_{jis} amount of fuel (bioethanol-gasoline blend) shipped from blending site in county $j \in N$ to distribution center in county $i \in N$ (gal)

Binary variables

b_{nj} equals 1 if a blending site with capacity level $n \in \{1,2,3,4,5,6\}, M3$ is set up in county $j \in N$

r^{N1}_{mi} equals 1 if a 1^{st} generation bio-refinery with capacity level $m \in M1$ is set up in county $i \in N$

r_{mi}^{N2} equals 1 if a 2^{nd} generation bio-refinery with capacity level $m \in M2$ is set up in county $i \in N$

Unrestricted variables

parameters

Harvesting sites

A_{js}^{C} amount of corn at county $j \in N$ in scenario $s \in S$ (MT)

A_{js}^{CS} amount of corn stover at county $j \in N$ in scenario $s \in S$ (MT)

F sustainability factor for harvesting site in each county

L feedstock loss factor due to baling and loading in each county

Bio-refineries and blending sites - design

B amount of loan to set up bio-refineries and blending sites in the state under study ($)

t loan payback period (y)

Φ interest rate of the loan received for establishing bio-refineries and blending sites

C_{m}^{N1} cost to set up a 1^{st} generation bio-refinery with capacity level $m \in M1$ ($)

C_{m}^{N2} cost to set up a 2^{nd} generation bio-refinery with capacity level $m \in M2$ ($)

W_n cost to set up a blending site with capacity level $n \in \{1,2,3,4,5,6\}, M3$ ($)

U_{i}^{E1} capacity of a 1^{st} generation bio-refinery at location $i \in E1$ (MT)

U_{i}^{E2} capacity of a 2^{nd} generation bio-refinery at location $i \in E2$ (MT)

U_{m}^{N1} capacity of a 1^{st} generation bio-refinery with capacity level $m \in M1$ (MT)

U_{m}^{N2} capacity of a 2^{nd} generation bio-refinery with capacity level $m \in M2$ (MT)

H_n capacity of a blending site with capacity level $n \in \{1,2,3,4,5,6\}, M3$ (gal)

Q lifetime of bio-refineries and blending sites (y)

Bio-refineries and blending sites - operation

C^{FEC} conversion cost per unit of corn based bioethanol produced ($\$/\text{gal}$)

C^{FECS} conversion cost per unit of corn stover based bioethanol produced ($\$/\text{gal}$)

V^{C} conversion factor for 1st generation bio-refineries (gal/MT)

V^{CS} conversion factor for 2nd generation bio-refineries (gal/MT)

C^{B} blending cost per unit of bioethanol-gasoline blend produced ($/gal)

E^{C} maximum amount of 1st generation bioethanol that can be imported from other states (gal)

E^{CS} maximum amount of 2nd generation bioethanol that can be imported from other states (gal)

J_s^{Co} number of jobs created annually per dollar of expenditures on construction of bio-refineries and blending sites in scenario $s \in S$ ($job/\$ \cdot \text{y}$)

J_s^{FE} number of jobs created annually per dollar of expenditures on conversion operation in scenario $s \in S$ ($job/\$ \cdot \text{y}$)

J_s^{CE} number of jobs created annually per dollar of expenditures on conversion of corn to bioethanol in scenario $s \in S$ ($job/\$ \cdot \text{y}$)

J_s^{CSE} number of jobs created annually per dollar of expenditures on conversion of corn stover to bioethanol in scenario $s \in S$ ($job/\$ \cdot \text{y}$)

J_s^{B} number of jobs created annually per dollar of expenditures on blending operation in scenario $s \in S$ ($job/\$ \cdot \text{y}$)

Unit prices

P_s^{C} price of corn purchased in scenario $s \in S$ ($\$/MT$)

P_s^{CS} price of corn stover purchased in scenario $s \in S$ ($\$/MT$)

P_s^{EC} price of corn based bioethanol sold to the exporter in scenario $s \in S$ ($\$/\text{gal}$)

P_s^{ECS} price of corn stover based bioethanol sold to the exporter in scenario $s \in S$ ($\$/\text{gal}$)

P_s^{EI} price of bioethanol purchased from other states in scenario $s \in S$ (\$/gal)

P_s^{IC} price of corn based bioethanol purchased from other states in scenario $s \in S$ (\$/gal)

P_s^{ICS} price of corn stover based bioethanol purchased from other states in scenario $s \in S$ (\$/gal)

P_s^{EE} price of bioethanol purchased from other countries in scenario $s \in S$ (\$/gal)

P_s^{FC} price of corn based bioethanol purchased from other countries in scenario $s \in S$ (\$/gal)

P_s^{FCS} price of corn stover based bioethanol purchased from other countries in scenario $s \in S$ (\$/gal)

P_s^{G} price of gasoline (from crude oil) purchased in scenario $s \in S$ (\$/gal)

P_s price of fuel (bioethanol-gasoline blend) sold to the distribution centers in scenario $s \in S$ (\$/gal)

P_s^{RC} price of corn based bioethanol RIN in scenario $s \in S$ ($\$/RIN$)

P_s^{RCS} price of corn stover based bioethanol RIN in scenario $s \in S$ ($\$/RIN$)

Distribution centers

D_{is} fuel (bioethanol-gasoline blend) demand at county $i \in N$ in scenario $s \in S$ (gal)

Transportation

C^{FTC} corn fixed transportation cost ($\$/MT$)

C_s^{VTC} corn variable transportation cost in scenario $s \in S$ ($\$/MT \cdot \text{mi}$)

C^{FTCS} corn stover fixed transportation cost ($\$/MT$)

C_s^{VTCS} corn stover variable transportation cost in scenario $s \in S$ ($\$/MT \cdot \text{mi}$)

C^{FTEG} fuel (bioethanol-gasoline blend) fixed transportation cost (\$/gal)

C_s^{VTEG} fuel (bioethanol-gasoline blend) variable transportation cost in scenario $s \in S$ ($\$/\text{gal} \cdot \text{mi}$)

C^{FTE} bioethanol fixed transportation cost ($\$/\text{gal}$)

C_s^{VTE} bioethanol variable transportation cost in scenario $s \in S$ ($\$/\text{gal} \cdot \text{mi}$)

d_{ij} direct distance from county i to county j (mi)

J_s number of jobs created for feedstock transported in scenario $s \in S$ ($job/MT \cdot \text{mi} \cdot \text{y}$)

J_s^{TC} number of jobs created for corn transported in scenario $s \in S$ ($job/MT \cdot \text{mi} \cdot \text{y}$)

J_s^{TCS} number of jobs created for corn stover transported in scenario $s \in S$ ($job/MT \cdot \text{mi} \cdot \text{y}$)

J_s^{TEG} number of jobs created for fuel transported in scenario $s \in S$ ($job/\text{gal} \cdot \text{mi} \cdot \text{y}$)

J_s^{TE} number of jobs created for bioethanol transported in scenario $s \in S$ ($job/\text{gal} \cdot \text{mi} \cdot \text{y}$)

τ tortuosity factor (for converting direct distance to real distance)

Policies

M_s^C amount of corn based bioethanol mandate for the state under study in scenario $s \in S$ (gal)

M_s^{CS} amount of corn stover based bioethanol mandate for the state under study in scenario $s \in S$ (gal)

$\overline{R}$ renewable fuel standard for first generation bioethanol

$\overline{\overline{R}}$ renewable fuel standard for second generation bioethanol

T tax credit per unit of bioethanol (locally produced and/or imported from other states) blended with gasoline (coming from crude oil) ($\$/\text{gal}$)

$\overline{T}$ tax credit per unit of bioethanol (imported from other countries) blended with gasoline (coming from crude oil) ($\$/\text{gal}$)

α	blend wall
β	coefficient of current bioethanol mandate
η	coefficient of current tax credit for blended bioethanol (that is locally produced and/or imported from other states)
θ	coefficient of current tax credit for blended bioethanol (that is imported from other countries)
RIN_s^C	amount of corn based bioethanol RINs for scenario $s \in S$
RIN_s^{CS}	amount of corn stover based bioethanol RINs for scenario $s \in S$

General

ω_s	probability of scenario $s \in S$

Objective function components

Revenues ($)

R^R	total expected revenue resulting from RINs sold
R^S	total expected revenue resulting from fuel (bioethanol-gasoline blend) sold
R^{TL}	total expected revenue resulting from tax credit for blended bioethanol (locally produced)
R^{TC}	total expected revenue resulting from tax credit for blended bioethanol (imported from other countries)
R^L	total expected revenue resulting from tax credit for the US blended bioethanol (locally produced)
R^I	total expected revenue resulting from tax credit for foreign blended bioethanol (imported from other countries)
R^{EE}	total expected revenue resulting from bioethanol sold to the exporter

Costs ($)

C^A	total cost resulting from the annual loan payback

C^{FP} total expected cost resulting from feedstock (corn stover) purchased

C^{F} total expected cost resulting from feedstock (corn and corn stover) purchased

C^{OC} total expected cost resulting from 1^{st} generation bio-refineries operation (conversion)

C^{OCS} total expected cost resulting from 2^{nd} generation bio-refineries operation (conversion)

C^{OB} total expected cost resulting from blending sites operation (blending)

C^{TF} total expected cost resulting from transportation of feedstock (corn stover)

C^{TE} total expected cost resulting from transportation of bioethanol from bio-refineries to blending sites

C^{T} total expected cost resulting from transportation of feedstock (corn stover), bioethanol and fuel

C^{TCE1} total expected cost resulting from transportation of corn to existing 1^{st} generation bio-refineries

C^{TCN1} total expected cost resulting from transportation of corn to new 1^{st} generation bio-refineries

C^{TCSE1} total expected cost resulting from transportation of corn stover to existing 2^{nd} generation bio-refineries

C^{TCSN1} total expected cost resulting from transportation of corn stover to new 2^{nd} generation bio-refineries

C^{TEE1} total expected cost resulting from transportation of bioethanol from existing 1^{st} generation bio-refineries to blending sites

C^{TEN1} total expected cost resulting from transportation of bioethanol from new 1^{st} generation bio-refineries to blending sites

C^{TEE2} total expected cost resulting from transportation of bioethanol from existing 2^{nd} generation bio-refineries to blending sites

C^{TEN2} total expected cost resulting from transportation of bioethanol from existing 2^{nd} generation bio-refineries to blending sites

C^{TEG} total expected cost resulting from transportation of fuel (bioethanol-gasoline blend) from blending sites to distribution centers

C^{I} total expected cost resulting from bioethanol imported from other states and other countries

C^{G} total expected cost resulting from gasoline (from crude oil) purchased

Profits ($)

G_1 total expected profits in Extended General Model (EGM)

L_1 total expected profits in Extended Lean Model (ELM)

Jobs (job)

J^{C} total expected number of jobs resulting from construction of bio-refineries and blending sites

J^{TF} total expected number of jobs resulting from transportation of feedstock

J^{TC} total expected number of jobs resulting from transportation of corn

J^{TCS} total expected number of jobs resulting from transportation of corn stover

J^{TE} total expected number of jobs resulting from transportation of bioethanol from bio-refineries to blending sites

J^{TEG} total expected number of jobs resulting from transportation of fuel (bioethanol-gasoline blend) from blending sites to distribution centers

J^{O} total expected number of jobs resulting from bio-refineries and blending sites operation (conversion and blending)

G_2 total expected number of jobs created in Extended General Model (EGM)

L_2 total expected number of jobs created in Extended Lean Model (ELM)

5.5.2 Aggregated Variables

The equations below represent the relationship between the variables of the Extended Lean Model (ELM) and Extended General Model (EGM). It is noticeable that in each equation, the aggregation of the variables over the locations would lead to one variable; however, the disaggregation of the variable may not be unique.

$$\sum_{i \in N} r_{mi}^{N1} = r_m^{N1}, \qquad \forall m \in M1 \tag{5.141}$$

$$\sum_{i \in N} r_{mi}^{N2} = r_m^{N2}, \qquad \forall m \in M2 \tag{5.142}$$

$$\sum_{j \in N} b_{nj} = r_m^{N1}, \qquad \forall n \in M3 \tag{5.143}$$

$$\sum_{j \in N} \sum_{i \in E1} f_{jis}^{E1} = f_s^{E1}, \qquad \forall s \in S \tag{5.144}$$

$$\sum_{j \in N} \sum_{(i=j) \cap (i \in E1)} f_{jis}^{E1} = f_s^{E1I}, \qquad \forall s \in S \tag{5.145}$$

$$\sum_{j \in N} \sum_{(i \neq j) \cap (i \in E1)} f_{jis}^{E1} = f_s^{E1E}, \qquad \forall s \in S \tag{5.146}$$

$$\sum_{j \in N} \sum_{i \in N} f_{jis}^{N1} = f_s^{N1}, \qquad \forall s \in S \tag{5.147}$$

$$\sum_{j\in N}\sum_{i=j} f_{jis}^{N1} = f_s^{N1I}, \qquad \forall s\in S \tag{5.148}$$

$$\sum_{j\in N}\sum_{(i\neq j)\cap(i\in N)} f_{jis}^{N1} = f_s^{N1E}, \qquad \forall s\in S \tag{5.149}$$

$$\sum_{j\in N}\sum_{i\in E2} f_{jis}^{E2} = f_s^{E2}, \qquad \forall s\in S \tag{5.150}$$

$$\sum_{j\in N}\sum_{(i=j)\cap(i\in E2)} f_{jis}^{E2} = f_s^{E2I}, \qquad \forall s\in S \tag{5.151}$$

$$\sum_{j\in N}\sum_{(i\neq j)\cap(i\in E2)} f_{jis}^{E2} = f_s^{E2E}, \qquad \forall s\in S \tag{5.152}$$

$$\sum_{j\in N}\sum_{i\in N} f_{jis}^{N2} = f_s^{N2}, \qquad \forall s\in S \tag{5.153}$$

$$\sum_{j\in N}\sum_{i=j} f_{jis}^{N2} = f_s^{N2I}, \qquad \forall s\in S \tag{5.154}$$

$$\sum_{j\in N}\sum_{(i\neq j)\cap(i\in N)} f_{jis}^{N2} = f_s^{N2E}, \qquad \forall s\in S \tag{5.155}$$

$$\sum_{i\in E1}\sum_{j\in N} e_{ijs}^{E1} = e_s^{E1}, \qquad \forall s\in S \tag{5.156}$$

$$\sum_{i\in E1}\sum_{j=i} e_{ijs}^{E1} = e_s^{E1I}, \qquad \forall s\in S \tag{5.157}$$

$$\sum_{i \in E1} \sum_{(j \neq i) \cap (j \in N)} e_{ijs}^{E1} = e_s^{E1E}, \qquad \forall s \in S \tag{5.158}$$

$$\sum_{i \in E2} \sum_{j \in N} e_{ijs}^{E2} = e_s^{E2}, \qquad \forall s \in S \tag{5.159}$$

$$\sum_{i \in E2} \sum_{j = i} e_{ijs}^{E2} = e_s^{E2I}, \qquad \forall s \in S \tag{5.160}$$

$$\sum_{i \in E2} \sum_{(j \neq i) \cap (j \in N)} e_{ijs}^{E2} = e_s^{E2E}, \qquad \forall s \in S \tag{5.161}$$

$$\sum_{i \in N} \sum_{j \in N} e_{ijs}^{N1} = e_s^{N1}, \qquad \forall s \in S \tag{5.162}$$

$$\sum_{i \in N} \sum_{j = i} e_{ijs}^{N1} = e_s^{N1I}, \qquad \forall s \in S \tag{5.163}$$

$$\sum_{i \in N} \sum_{(j \neq i) \cap (j \in N)} e_{ijs}^{N1} = e_s^{N1E}, \qquad \forall s \in S \tag{5.164}$$

$$\sum_{i \in N} \sum_{j \in N} e_{ijs}^{N2} = e_s^{N2}, \qquad \forall s \in S \tag{5.165}$$

$$\sum_{i \in N} \sum_{j = i} e_{ijs}^{N2} = e_s^{N2I}, \qquad \forall s \in S \tag{5.166}$$

$$\sum_{i \in N} \sum_{(j \neq i) \cap (j \in N)} e_{ijs}^{N2} = e_s^{N2E}, \qquad \forall s \in S \tag{5.167}$$

$$\sum_{i \in E1} o_{is}^{E1} = o_s^{E1}, \qquad \forall s \in S \tag{5.168}$$

$$\sum_{i \in E2} o_{is}^{E2} = o_s^{E2}, \qquad \forall s \in S \tag{5.169}$$

$$\sum_{i \in N} o_{is}^{N1} = o_s^{N1}, \qquad \forall s \in S \tag{5.170}$$

$$\sum_{i \in N} o_{is}^{N2} = o_s^{N2}, \qquad \forall s \in S \tag{5.171}$$

$$\sum_{j \in N} h_{js}^{C} = h_s^{C}, \qquad \forall s \in S \tag{5.172}$$

$$\sum_{j \in N} h_{js}^{CS} = h_s^{CS}, \qquad \forall s \in S \tag{5.173}$$

$$\sum_{j \in N} k_{js}^{C} = k_s^{C}, \qquad \forall s \in S \tag{5.174}$$

$$\sum_{j \in N} k_{js}^{CS} = k_s^{CS}, \qquad \forall s \in S \tag{5.175}$$

$$\sum_{j \in N} g_{js} = g_s, \qquad \forall s \in S \tag{5.176}$$

$$\sum_{j \in N} \sum_{j \in N} x_{jis} = x_s, \qquad \forall s \in S \tag{5.177}$$

$$\sum_{j \in N} \sum_{i=j} x_{jis} = x_s^I, \qquad \forall s \in S \tag{5.178}$$

$$\sum_{j \in N} \sum_{(i \neq j) \cap (i \in N)} x_{jis} = x_s^E, \qquad \forall s \in S \tag{5.179}$$

Apart from the variables, there are following parameters which get aggregated during converting ELM to EGM:

- Corn supply

$$\sum_{j \in N} A_{js}^C = A_s^C, \qquad \forall s \in S \tag{5.180}$$

- Corn stover supply

$$\sum_{j \in N} A_{js}^{CS} = A_s^{CS}, \qquad \forall s \in S \tag{5.181}$$

- Fuel demand

$$\sum_{i \in N} D_{is} = D_s, \qquad \forall s \in S \tag{5.182}$$

- Capacity of bio-refinery using corn

$$\sum_{i \in E1} U_i^{E1} = U^{E1} \tag{5.183}$$

- Capacity of bio-refinery using corn stover

$$\sum_{i \in E2} U_i^{E2} = U^{E2} \tag{5.184}$$

5.5.3 Proofs of Relationship Between EGM and ELM

Proof. *Observation 6* – If Y satisfies constraints (5.4)-(5.24) of the EGM, X satisfies the mirror constraints (5.61)-(5.75) and (5.104)-(5.107) of the ELM resulting from the aggregation over the counties. Note that the constraints (5.14) and (5.15) in the EGM do not have any counterpart in the ELM, as they are omitted during simplification process. In contrast, the constraints (5.76)-(5.103) in the ELM do not exist in the EGM explicitly; they are added in the ELM in order to obtain more accurate solutions, which are closer approximations of their counterparts in the EGM. Below we prove these constraints, (5.76)-(5.103), do not prevent converting Y to X:

- The constraints (5.76)-(5.84): By definitions in Appendix 5.5.2: (5.147), (5.148) and (5.149) imply (5.76) for the corn flow from HSG1s to BRN1s in X; (5.153), (5.154) and (5.155) imply (5.77) for the corn stover flow from HSG2s to BRN2s in X; (5.162), (5.163) and (5.164) imply (5.78) for the 1^{st} generation bioethanol flow from BRN1s to BLs in X; (5.165), (5.166) and (5.167) imply (5.79) for the 2^{nd} generation bioethanol flow from BRN2s to BLs in X; (5.168)-(5.179) along with the constraints (5.14) and (5.15) met for Y imply (5.80) for the fuel flow from BLs to DCs in X; (5.144), (5.145) and (5.146) imply (5.81) for the corn flow from HSG1s to BRE1s in X; (5.150), (5.151) and (5.152) imply (5.82) for the corn stover flow from HSG2s to BRE2s in X; (5.156), (5.157) and (5.158) imply (5.83) for the 1^{st} generation bioethanol flow from BRE1s to BLs in X; (5.159), (5.160) and (5.161) imply (5.84) for the 2^{nd} generation bioethanol flow from BRE2s to BLs in X;

- The constraints (5.85)-(5.86), (5.88)-(5.89) and (5.91)-(5.92): By setting $S^{N1}_{mj} := r^{N1}_{mi}$, $S^{N2}_{mj} := r^{N2}_{mi}$, and $T_{nj} := b_{nj}$: (1) if Y satisfies the constraints (5.1)-(5.3) of the EGM hold, X meets the constraints (5.86), (5.89) and (5.92) of the ELM; (2) the definitions (5.141)-(5.143) in Appendix 5.5.2 imply the constraints (5.85), (5.88) and (5.91) in the ELM.

- The constraints (5.95)-(5.96) and (5.98)-(5.99): We set $P^{N1}_{mnj} = 1$ if and only if $S^{N1}_{mj} = 1$ and $T_{nj} = 1$ for all $m \in M1$, $n \in M3$, and $j \in N$. Thus, $P^{N1}_{mnj} = 1$ if a BRN1 of size U^{N1}_m and a BL size H_n are both established in county j. Likewise, we set $P^{N2}_{mnj} = 1$ if and only if $S^{N2}_{mj} = 1$ and $T_{nj} = 1$ for all $m \in M2$, $n \in M3$, and $j \in N$. Thus, $P^{N2}_{mnj} = 1$ if a BRN2 of size U^{N2}_m and a BL size H_n are both established in county j. By setting $S^{N1}_{mj} := r^{N1}_{mi}$, $S^{N2}_{mj} := r^{N2}_{mi}$, and $T_{nj} := b_{nj}$, along with the definitions (5.141)-(5.143) in Appendix 5.5.2 imply the constraints (5.95)-(5.96) and (5.98)-(5.99) in the ELM.

- The constraints (5.87), (5.90), (5.100) and (5.101): The maximum amount of corn shipped from a HSG1 to a BRN1 of size U^{N1}_m, both located in the same county $j \in N$, equals to $B^{N1}_{mjs} = \min\{A^C_{js} \cdot (1-L), U^{N1}_m\}$ for $m \in M1$, $j \in N$, and $s \in S$. Thus, the actual amount of corn, f^{N1I}_s, by definition (5.148), shipped in Y satisfies the constraint (5.87) in X. Likewise, the maximum amount of corn stover shipped from a HSG2 to a BRN2 of size U^{N2}_m, both located in the same county $j \in N$, equals to $B^{N2}_{mjs} = \min\{A^{CS}_{js} \cdot (1-L) \cdot (1-F), U^{N2}_m\}$ for $m \in M2$, $j \in N$, and $s \in S$. Thus, the actual amount of corn stover, f^{N2I}_s, by definition (5.154), shipped in Y satisfies the constraint (5.90) in X. Furthermore, the maximum amount of corn shipped from a HSG1 to a BRE1 of size U^{E1}_m, both located in the same county $i \in E1$, equals to $\min\{U^{E1}_i, (1-L) \cdot A^C_{is}\}$ for $i \in E1$ and $s \in S$. Thus, the actual amount of corn, f^{E1I}_s, by definition (5.145), shipped in Y satisfies the constraint (5.100) in X. Moreover, the maximum amount of corn stover shipped from a HSG2 to a BRE2 of size U^{E2}_m, both located in the same county $i \in E2$, equals to $\min\{U^{E2}_i, (1-L) \cdot A^{CS}_{is}\}$ for $i \in E2$ and $s \in S$. Thus, the actual amount of corn stover, f^{E2I}_s, by definition (5.151), shipped in Y satisfies the constraint (5.101) in X.

- The constraints (5.93), (5.94), (5.97), (5.102), and (5.103): The maximum amount of fuel shipped from a BL size H_n to a DC with demand D_{js}, both located in the same county $j \in N$, equals to $C_{njs} = \min\{D_{js}, H_n\}$ for $n \in M3$, $j \in N$, and $s \in S$. Thus, the actual amount of fuel, x_s^I, by definition (5.178), shipped in Y satisfies the constraint (5.93) in X. Likewise, the maximum amount of 1^{st} generation bioethanol shipped from a BRN1 of size $U_m^{N1}$to a BL of size H_n, both located in the same county $j \in N$, equals to $E_{mn}^{N1} = \min\{V^C \cdot U_m^{N1}, \alpha \cdot H_n\}$ for $m \in M1$, and $n \in M3$. Thus, the actual amount of 1^{st} generation bioethanol, e_s^{N1I}, by definition (5.163), shipped in Y satisfies the constraint (5.94) in X. Furthermore, the maximum 2^{nd} generation bioethanol shipped from a BRN2 of size U_m^{N2} to a BL of size H_n equals to $E_{mn}^{N2} = \min\{V^{CS} \cdot U_m^{N2}, \alpha \cdot H_n\}$ for $m \in M2$, and $n \in M3$. Thus, the actual amount of 2^{nd} generation bioethanol, e_s^{N2I}, by definition (5.166), shipped in Y satisfies the constraint (5.97) in X. Moreover, the maximum amount of 1^{st} generation bioethanol shipped from a BRE1 of size U_i^{E1} to a BL of size H_n, both located in the same county $i \in E1$, equals to $A_{ni}^{E1} = \min\{V^C \cdot U_i^{E1}, \alpha \cdot H_n\}$ for $i \in E1$, and $n \in M3$. Thus, the actual amount of corn stover, e_s^{E1I}, by definition (5.157), shipped in Y satisfies the constraint (5.102) in X. Similarly, the maximum amount of 2^{nd} generation bioethanol shipped from a BRE2 of size U_i^{E2} to a BL of size H_n, both located in the same county $i \in E2$, equals to $A_{ni}^{E2} = \min\{V^{CS} \cdot U_i^{E2}, \alpha \cdot H_n\}$ for $i \in E2$, and $n \in M3$. Thus, the actual amount of corn stover, e_s^{E2I}, by definition (5.151), shipped in Y satisfies the constraint (5.103) in X.

■

Proof. *Observation 7* –We disaggregate X as follows: first, locate the $\sum_{m \in M1} r_{mi}^{N1}$ of BRN1s, $\sum_{m \in M2} r_{mi}^{N2}$ of BRN2s, in the $\sum_{m \in M1} r_{mi}^{N1}$ and $\sum_{m \in M2} r_{mi}^{N2}$ counties respectively in a way that, if $S_{mj}^{N1} = 1$ and $S_{mj}^{N2} = 1$ respectively, establish a BRN1 of size U_m^{N1} and a BRN2 of size U_m^{N2} in county j. Second, locate the $\sum_{n \in M3} b_{nj}$ of blending sites in the $\sum_{n \in M3} b_{nj}$ counties as follows: if $T_{nj} = 1$ locate a blending site of size H_n in county j. Clearly constraints (5.85)-(5.86), (5.88)-(5.89), and (5.91)-(5.92) in the ELM ensure such locations satisfy the constraints (5.1)-(5.3) of the EGM. Since X satisfies the budged constraint (5.61) so does the disaggregated solution. Thus (5.4) is satisfied.

Let $Bio1$, $Bio2$ and Bl be the sets of counties with BRN1s, BRN2s, and BLs that result from the disaggregation. To systematically prove the disaggregation of flows to/from the new facilities (BRN1s, BRN2s, and BLs) and existing ones (HSG1s, HSG2s, BRE1s, BRE2s, and DCs), we classify them in the following categories:

1. Flow of corn from HSG1s to BRN1s, and then flow of 1^{st} generation bioethanol from BRN1s to BLs – In order to disaggregate the flow of corn from HSG1s to BRN1s, by constraint (5.87) in the ELM, we obtain

$$\sum_{i \in Bio1} \min\{A_{is}^{C} \cdot (1-L), U_i^{N1}\} \geq f_s^{N1I} \tag{5.185}$$

   which ensures the locations in $Bio1$ guarantee the flow of corn f_s^{N1I} satisfying X, where U_i^{N1} is the size of bio-refinery in county $i \in Bio1$. Thus, for any scenario $s \in S$, we can obtain the internal flow f_{iis}^{N1} for each county i such a that $\sum_{i \in Bio1} f_{iis}^{N1} = f_s^{N1I}$. According to the internal corn flows f_{iis}^{N1} we can determine the external corn flow f_{jis}^{N1} for $j \in N$ and $(i \neq j) \cap (i \in N)$ for Y, so that $\sum_{j \in N} \sum_{(i \neq j) \cap (i \in N)} f_{jis}^{N1} = f_s^{N1E}$, for any scenario $s \in S$. The corn flow f_{jis}^{N1} can be determined by solving a cost minimization network flow problem N^{fN1} given f_s^{N1I} and f_s^{N1E}; the capacities of the nodes in the network (corn supply from county j and a BRN1 at county i) are determined by constraints (5.5) and (5.8). The obtained corn flows f_{jis}^{N1} are feasible for Y given constraints (5.62), (5.73) and (5.76). Then, given f_{iis}^{N1}, we calculate the amount of bioethanol $V^C \cdot f_{iis}^{N1}$ produced by a BRN1 located in county i, which is an upper bound for the amount of bioethanol e_{iis}^{N1} produced in county i and used in the state. Accordingly, we can calculate e_{ijs}^{N1} for $i \in N$ and $(j \neq i) \cap (j \in N)$ for the Y, so that $\sum_{i \in N} \sum_{(j \neq i) \cap (j \in N)} e_{ijs}^{N1} = e_{s}^{N1E}$, for any scenario $s \in S$. Also, we can solve a cost minimization network problem N^{G1N1} to determine bioethanol flows e_{ijs}^{N1} consistent with the corn flows f_{jis}^{N1}, which satisfy the constraint (5.8) in the EGM given the constraint (5.65) in the ELM.

2. Flow of corn from HSG1s to BRE1s, and then flow of 1^{st} generation bioethanol from BRE1s to BLs – In order to disaggregate the flow of corn from HSG1s to BRE1s, the constraint (5.101) in the ELM ensures the locations in $E1$ guarantee the flow of corn f_{s}^{E1I} satisfying X. Thus, for any scenario $s \in S$, we can obtain the internal flow f_{iis}^{E1} for each county i such a that $\sum_{i \in E1} f_{iis}^{E1} = f_{s}^{E1I}$. According to the internal corn flows f_{iis}^{E1} we can determine the external corn flow f_{jis}^{E1} for $j \in N$ and $(i \neq j) \cap (i \in E1)$ for Y, so that $\sum_{j \in N} \sum_{(i \neq j) \cap (i \in E1)} f_{jis}^{E1} = f_{s}^{E1E}$, for any scenario $s \in S$. The corn flow f_{jis}^{E1} can be determined by solving a cost minimization network flow problem N^{fE1} given f_{s}^{E1I} and f_{s}^{E1E}. The obtained corn flows f_{jis}^{E1} are feasible for Y given constraints (5.62), (5.71) and (5.81). Then, given f_{iis}^{E1}, we calculate the amount of bioethanol $V^{C} \cdot f_{iis}^{E1}$ produced by a BRE1 located in county $i \in E1$, which is an upper bound for the amount of bioethanol e_{iis}^{E1} produced in the county $i \in E1$ and used in the state. Accordingly, we can calculate e_{ijs}^{E1} for $i \in E1$ and $(j \neq i) \cap (j \in N)$ for Y, so that $\sum_{i \in E1} \sum_{(j \neq i) \cap (j \in N)} e_{ijs}^{E1} = e_{s}^{E1E}$, for any scenario $s \in S$. Also, we can solve a cost minimization network problem N^{G1E1} to determine bioethanol flows e_{ijs}^{E1} consistent with the corn flows f_{jis}^{E1}, which satisfy the constraint (5.7) in the EGM given the constraint (5.64) in the ELM.

3. Flow of corn stover from HSG2s to BRN2s, and then flow of 2^{nd} generation bioethanol from BRN2s to BLs – In order to disaggregate the flow of corn stover from HSG2s

to BRN2s, by constraint (5.87) in the ELM, we obtain

$$\sum_{i \in Bio2} \min\{A_{is}^{C} \cdot (1-L), U_i^{N2}\} \geq f_s^{N2I} \tag{5.186}$$

which ensures the locations in $Bio2$ guarantee the flow of corn stover f_s^{N2I} satisfying X, where U_i^{N2} is the size of bio-refinery in county $i \in Bio2$. Thus, for any scenario $s \in S$, we can obtain the internal flow f_{iis}^{N2} for each county i such a that $\sum_{i \in Bio2} f_{iis}^{N2} = f_s^{N2I}$. According to the internal corn stover flows f_{iis}^{N2} we can determine the external corn stover flow f_{jis}^{N2} for $j \in N$ and $(i \neq j) \cap (i \in N)$ for the Y, so that $\sum_{j \in N} \sum_{(i \neq j) \cap (i \in N)} f_{jis}^{N2} = f_s^{N2E}$, for any scenario $s \in S$. The corn stover flow f_{jis}^{N2} can be determined by solving a cost minimization network flow problem N^{fN2} given f_s^{N2I} and f_s^{N2E}. The obtained corn stover flows f_{jis}^{N1} are feasible for Y given constraints (5.63), (5.74) and (5.77). Then, given f_{iis}^{N2}, we calculate the amount of bioethanol $V^{CS} \cdot f_{iis}^{N2}$ produced by a BRN2 located in county i, which is an upper bound for the amount of bioethanol e_{iis}^{N2} produced in county i and used in the state. Accordingly, we can calculate e_{ijs}^{N2} for $i \in N$ and $(j \neq i) \cap (j \in N)$ for the Y, so that $\sum_{i \in N} \sum_{(j \neq i) \cap (j \in N)} e_{ijs}^{N2} = e_s^{N2E}$, for any scenario $s \in S$. Also, we can solve a cost minimization network problem N^{G2N1} to determine bioethanol flows e_{ijs}^{N2} consistent with the corn stover flows f_{jis}^{N2}, which satisfy the constraint (5.10) in the EGM given the constraint (5.67) in the ELM.

4. Flow of corn stover from HSG2s to BRE2s, and then flow of 2^{nd} generation bioethanol from BRE2s to BLs – In order to disaggregate the flow of corn stover from HSG2s to BRE2s, constraint (5.102) in the ELM ensures the locations in $E2$ guarantee the flow of corn stover f_s^{E2I} satisfying X, where U_i^{E2} is the size of the bio-refinery in county $i \in E2$. Thus, for any scenario $s \in S$, we can obtain the internal flow f_{iis}^{E2} for each county $i \in E2$ such a that $\sum_{i \in E2} f_{iis}^{E2} = f_s^{E2I}$. According to the internal corn

stover flows f^{E2}_{iis} we can determine the external corn stover flow f^{E2}_{jis} for $j \in N$ and $(i \neq j) \cap (i \in E2)$ for the Y, so that $\sum_{j \in N} \sum_{(i \neq j) \cap (i \in E2)} f^{E2}_{jis} = f^{E2E}_{s}$, for any scenario $s \in S$. The corn stover flow f^{E2}_{jis} can be determined by solving a cost minimization network flow problem N^{fE2} given f^{E2I}_{s} and f^{E2E}_{s}. The obtained corn stover flows f^{E2}_{jis} are feasible for Y given constraints (5.63), (5.74) and (5.77). Then, given f^{E2}_{iis}, we calculate the amount of bioethanol $V^{CS} \cdot f^{E2}_{iis}$ produced by a BRE2 located in county $i \in E2$, which is an upper bound for the amount of bioethanol e^{E2}_{iis} produced in county $i \in E2$ and used in the state. Accordingly, we can calculate e^{E2}_{ijs} for $i \in E2$ and $(j \neq i) \cap (j \in N)$ for the Y, so that $\sum_{i \in E2} \sum_{(j \neq i) \cap (j \in N)} e^{E2}_{ijs} = e^{E2E}_{s}$, for any scenario $s \in S$. Also, we can solve a cost minimization network problem N^{G2E2} to determine bioethanol flows e^{E2}_{ijs} consistent with the corn stover flows f^{E2}_{jis}, which satisfy the constraint (5.10) in the EGM given the constraint (5.67) in the ELM.

5. Flow of fuel from BLs to DCs – In order to disaggregate the flow of fuel, by constraint (5.93) in the ELM, we obtain

$$\sum_{i \in Bl} \min\{D_{is}, H_i\} \geq x^{I}_{s}, \tag{5.187}$$

which ensures the locations in Bl guarantee the flow of fuel x^{I}_{s} satisfying X, where H_i is the size of blending site in county $i \in Bl$. Thus, for any scenario $s \in S$, we can obtain the internal flow x_{iis} for each county i such a that $\sum_{i \in Bl} x_{iis} = x^{I}_{s}$. According to the internal fuel flows x_{iis} we can determine the external corn fuel flow x_{jis} for $j \in N$ and $(i \neq j) \cap (i \in N)$ for Y, so that $\sum_{j \in N} \sum_{(i \neq j) \cap (i \in N)} x_{jis} = x^{E}_{s}$, for any scenario $s \in S$. The fuel flow x_{jis} can be determined by solving a cost minimization network flow problem N^{f} given x^{I}_{s} and x^{E}_{s}. The obtained fuel flows x_{jis} are feasible for Y given constraint (5.80). The fuel flows also determine the amount of fuel x_{jjs} produced in county j which will subsequently serve as the upper limit on the amount of bioethanol e_{jjs}^{N1}, e_{jjs}^{E1}, e_{jjs}^{N2}, and e_{jjs}^{E2} respectively in the network flow problems N^{G1N1}, N^{G1E1}, N^{G2N2}, and N^{G2E2} used to calculate bioethanol flows consistent with the fuel flows x_{jis} in order to satisfy constraint (5.14) in Y by (5.80) in X.

So far we have explained how to obtain feasible material flows for: corn (f_{jis}^{N1}, and f_{jis}^{E1}), corn stover (f_{jis}^{N2}, and f_{jis}^{E2}), 1st generation bioethanol (e_{ijs}^{N1} and e_{ijs}^{E1}), and 2nd generation bioethanol (e_{ijs}^{N2}, and e_{ijs}^{E2}). However, there are other material flows in the SCOSC, which are sold to the exporters or purchased from importers and refineries: selling 1st generation bioethanol (o_{is}^{N1} and o_{is}^{E1}) to bioethanol exporters (EE1s), selling 2nd generation bioethanol (o_{is}^{N2}, and o_{is}^{E2}) to bioethanol exporters (EE2s), purchasing 1st generation bioethanol from other states and abroad (h_{is}^{C} and k_{is}^{C} respectively), purchasing 2nd generation bioethanol from other states and abroad (h_{is}^{CS} and k_{is}^{CS} respectively), and purchasing gasoline (g_{is}) from gasoline importers and refineries. To obtain a feasible solution for each of these flows we proceed as follows:

- For o_{is}^{N1} and o_{is}^{E1} – by using two constraints (5.8) and (5.18), three equations (5.147), (5.162), and (5.65), and solving a profit maximization network flow problem, we obtain o_{is}^{N1} for Y such that it satisfies constraint (5.8). Similarly, by employing two constraints (5.7) and (5.16), three equations (5.144), (5.156), and (5.64), and solving a profit maximization network flow problem, we obtain o_{is}^{E1} for Y such that it satisfies constraint (5.7).

- For o_{is}^{N2}, and o_{is}^{E2} – by employing two constraints (5.10) and (5.19), and three equations (5.153), (5.165), and (5.67), and solving a profit maximization network flow problem, we obtain o_{is}^{N2} for Y such that it satisfies constraint (5.10). Similarly, by employing two constraints (5.9) and (5.17), three equations (5.150), (5.165), and

(5.66), and solving a profit maximization network flow problem, we obtain o_{is}^{E2} for Y such that it satisfies constraint (5.9).

- For h_{is}^{C}, k_{is}^{C}, h_{is}^{CS}, k_{is}^{CS}, and g_{is} – by constraints (5.11)-(5.15), equations (5.153-(5.165) and (5.172)-(5.178), we can obtain h_{is}^{C}, k_{is}^{C}, h_{is}^{CS}, k_{is}^{CS}, and g_{is}. Thus Y satisfies constraints (5.11)-(5.15), since X satisfies constraints (5.68)-(5.70).

Note that the solution is not unique since the material flows, for instance, can be calculated differently. ■

Proof. *Observation 8* – Given Observation 6, a feasible solution Y for the EGM can be converted to a feasible solution X for the ELM. If we replace $\bar{d} = \delta$, $\bar{d}^{E1} = \gamma$, and $\bar{d}^{E2} = \lambda$ in $G_1(Y)$ of the EGM, see expected cost components (5.120)-(5.128) of the ELM objective function, we obtain $L_1(X)$ of the ELM. However, for scenario $s \in S$

$$
\begin{aligned}
&\delta \cdot f_s^{N1E} \leq \sum_{j \in N} \sum_{(i \neq j) \cap (i \in N)} f_{jis}^{N1} \cdot d_{ji}, \\
&\delta \cdot f_s^{N2E} \leq \sum_{j \in N} \sum_{(i \neq j) \cap (i \in N)} f_{jis}^{N1} \cdot d_{ji}, \\
&\delta \cdot e_s^{N1E} \leq \sum_{i \in N} \sum_{(j \neq i) \cap (j \in N)} e_{ijs}^{N1} \cdot d_{ij}, \\
&\delta \cdot e_s^{N2E} \leq \sum_{i \in N} \sum_{(j \neq i) \cap (j \in N)} e_{ijs}^{N2} \cdot d_{ij}, \\
&\delta \cdot x_s^{E} \leq \sum_{j \in N} \sum_{(i \neq j) \cap (i \in N)} x_{jis} \cdot d_{ji}, \\
&\gamma \cdot f_s^{E1E} \leq \sum_{j \in N} \sum_{(i \neq j) \cap (i \in E1)} f_{jis}^{E1} \cdot d_{ji}, \\
&\lambda \cdot f_s^{E2E} \leq \sum_{j \in N} \sum_{(i \neq j) \cap (i \in E2)} f_{jis}^{E2} \cdot d_{ji}, \\
&\gamma \cdot e_s^{E1E} \leq \sum_{i \in E1} \sum_{(j \neq i) \cap (j \in N)} e_{ijs}^{E1} \cdot d_{ij}, \\
&\lambda \cdot e_s^{E2E} \leq \sum_{i \in E2} \sum_{(j \neq i) \cap (j \in N)} e_{ijs}^{E2} \cdot d_{ij}.
\end{aligned}
$$

Therefore, $L_1(X) \geq G_1(Y)$. Additionally, for an optimal solution $X_{\min}$ to the ELM we have $L_1(X_{\min}) \geq L_1(X)$. Thus, we conclude $L_1(X_{\min}) \geq G_1(Y)$.

Likewise, given Observation 7, an optimal solution $X_{\max}$ for the ELM can be converted to a feasible solution Y' to the EGM. If we replace $\bar{d} = \Delta$, $\bar{d}^{E1} = \Gamma$, and $\bar{d}^{E2} = \Lambda$ in $G_1(Y')$ of the EGM, see expected cost components (5.120)-(5.128) of the ELM objective function, we obtain $L_1(X_{\max})$ of the ELM. However, for scenario $s \in S$

$$\Delta \cdot f_s^{N1E} \geq \sum_{j \in N} \sum_{(i \neq j) \cap (i \in N)} f_{jis}^{N1} \cdot d_{ji},$$
$$\Delta \cdot f_s^{N2E} \geq \sum_{j \in N} \sum_{(i \neq j) \cap (i \in N)} f_{jis}^{N1} \cdot d_{ji},$$
$$\Delta \cdot e_s^{N1E} \geq \sum_{i \in N} \sum_{(j \neq i) \cap (j \in N)} e_{ijs}^{N1} \cdot d_{ij},$$
$$\Delta \cdot e_s^{N2E} \geq \sum_{i \in N} \sum_{(j \neq i) \cap (j \in N)} e_{ijs}^{N2} \cdot d_{ij},$$
$$\Delta \cdot x_s^{E} \geq \sum_{j \in N} \sum_{(i \neq j) \cap (i \in N)} x_{jis} \cdot d_{ji},$$
$$\Gamma \cdot f_s^{E1E} \geq \sum_{j \in N} \sum_{(i \neq j) \cap (i \in E1)} f_{jis}^{E1} \cdot d_{ji},$$
$$\Lambda \cdot f_s^{E2E} \geq \sum_{j \in N} \sum_{(i \neq j) \cap (i \in E2)} f_{jis}^{E2} \cdot d_{ji},$$
$$\Gamma \cdot e_s^{E1E} \geq \sum_{i \in E1} \sum_{(j \neq i) \cap (j \in N)} e_{ijs}^{E1} \cdot d_{ij},$$
$$\Lambda \cdot e_s^{E2E} \geq \sum_{i \in E2} \sum_{(j \neq i) \cap (j \in N)} e_{ijs}^{E2} \cdot d_{ij}.$$

Therefore, $G_1(Y') \geq L_1(X_{\max})$. Furthermore, for an optimal solution Y to the EGM, we have $G_1(Y) \geq G_1(Y')$. Thus, we conclude $G_1(Y) \geq L_1(X_{\max})$. ■

Proof. *Observation 9* – The proof is similar to the proof of Observation 8, thus it is omitted.

■

Proof. *Observation 10* – By Observation 6, Y can be converted into a feasible solution X to the ELM. The only difference between $L_1^{\delta,\gamma,\lambda}(X) + L_2^{\Delta}(X)$ and $G_1(Y) + G_2(Y)$ consists of replacing the distances $\bar{d} = \delta$, $\bar{d}^{E1} = \gamma$, and $\bar{d}^{E2} = \lambda$ in the objective L_1 and $\bar{d} = \Delta$ in the objective L_2; please check the objective function components (5.120)-(5.128) and (5.135)-(5.138) in the ELM. Therefore, $L_1^{\delta,\gamma,\lambda}(X) + L_2^{\Delta}(X) \geq G_1(Y) + G_2(Y)$. For an optimal solution Y_{max} we have $L_1^{\delta,\gamma,\lambda}(Y_{max}) + L_2^{\Delta}(Y_{max}) \geq L_1^{\delta,\gamma,\lambda}(X) + L_2^{\Delta}(X) \geq G_1(Y) + G_2(Y)$.

By Observation 7, Y_{min} can be converted into a feasible solution Y' to the EGM. The only difference between $L_1^{\Delta,\Gamma,\Lambda}(X)+L_2^{\delta}(X)$ and $G_1(Y')+G_2(Y')$ consists of replacing the distances $\bar{d}=\Delta$, $\bar{d}^{E1}=\Gamma$, and $\bar{d}^{E2}=\Lambda$ in the objective L_1 and $\bar{d}=\delta$ in the objective L_2; please again check the objective function components (5.120)-(5.128) and (5.135)-(5.138) in the ELM. Therefore, $L_1^{\Delta,\Gamma,\Lambda}(X)+L_2^{\delta}(X)\leq G_1(Y')+G_2(Y')$. For an optimal solution Y we have $L_1^{\Delta,\Gamma,\Lambda}(Y_{min})+L_2^{\delta}(Y_{min})\leq G_1(Y')+G_2(Y')\leq G_1(Y)+G_2(Y)$. ■

Proof. *Observation 11* – The cost function for bio-refineries/blending sites, $C(k)=k^{0.6}\cdot C(1)$ for $k=\frac{U_k}{U_1}$, where U_k is capacity of a facility whose capacity level is k times the base capacity U_1, is strictly concave Wright and Brown (2007) . Therefore, if there are two feasible solutions to the ELM, one with $k=a,b$ $(1\leq a\leq b)$, the other one with $k=a-\delta,b+\delta$ for $\delta>0$, the latter one is better. Since,

$$C(a)+C(b)>C(a-\delta)+C(b+\delta) \tag{5.188}$$

and the annual loan payment for the second solution is less than and equal to the first solution, $C^A(a,b)>C^A(a-\delta,b+\delta)$. To show this according to the definition of the strictly concave function, $f(\lambda\cdot X_1+(1-\lambda)\cdot X_2)>\lambda\cdot f(X_1)+(1-\lambda)\cdot f(X_2)$, we assume $l=b+\delta-a$, then

$C(b)>(\frac{l-\delta}{l})\cdot C(b+\delta)+(\frac{\delta}{l})\cdot C(a)$

and from this we derive

$C(b)-C(a)>(\frac{l-\delta}{\delta})\cdot[C(b+\delta)-C(b)]$

Similarly,

$C(a)>(\frac{l-\delta}{l})\cdot C(a-\delta)+(\frac{\delta}{l})\cdot C(b)$

and so

$C(b)-C(a)<(\frac{l-\delta}{\delta})\cdot[C(a)-C(a-\delta)]$

Therefore, we can see

$(\frac{l-\delta}{\delta}) \cdot [C(b+\delta) - C(b)] < C(b) - C(a) < (\frac{l-\delta}{\delta}) \cdot [C(a) - C(a-\delta)]$

Finally, $C(b+\delta) - C(b) < C(a) - C(a-\delta)$, which is $C(a) + C(b) > C(a-\delta) + C(b+\delta)$. However, flow constraints (5.85)-(5.87) do not allow utilizing the concavity property. For instance, let us compare the two solutions below, with the assumption that (1) for the first two levels, $m = 1, 2$, the capacity of 1^{st} generation bio-refineries are $U_1^{N1} = 200$, $U_2^{N1} = 400$ Mgal/y, and (2) supply of corn, $(1-L) \cdot A_{js}^C$, is 160 and 140 Mbu/y from the two counties with the highest amount of annual corn production.

1. $r_1^{N1} = 2$, $r_2^{N1} = 0$, $r_3^{N1} = 0$. By constraint (5.85) in the ELM

$$\sum_{j \in N} S_{1j}^{N1} = 2, \sum_{j \in N} S_{2j}^{N1} = \sum_{i \in N} S_{3j}^{N1} = 0 \tag{5.189}$$

also by constraint (5.86) in the ELM

$$S_{1j}^{N1} + S_{2j}^{N1} + S_{3j}^{N1} \leq 1, \forall j \in N \implies S_{1j}^{N1} \leq 1, \forall j \in N \tag{5.190}$$

Thus by constraint (5.87) and $B_{1js}^{N1} = \min\{A_{js}^C \cdot (1-L), U_1^{N1} = 200\}$, we obtain $f_s^{N1I} \leq \sum_{j \in N} \sum_{m \in M1} B_{mjs}^{N1} \cdot S_{mj}^{N1} = 300$. In other words, if two 1^{st} generation bio-refineries with capacity $U_1^{N1} = 200$ get set up at two different counties with 160 and 140 Mgal/y corn production annually, they can handle the total internal flow, 300 Mbu/y.

2. $r_1^{N1} = 0$, $r_2^{N1} = 1$, $r_3^{N1} = 0$. By constraint (5.85) in the ELM

$$\sum_{j \in N} S_{1j}^{N1} = 0, \sum_{j \in N} S_{2j}^{N1} = 1, \sum_{i \in N} S_{3j}^{N1} = 0 \tag{5.191}$$

also by constraint (5.86) in the ELM

$$S_{1j}^{N1} + S_{2j}^{N1} + S_{3j}^{N1} \leq 1, \forall j \in N \implies S_{2j}^{N1} \leq 1, \forall j \in N \tag{5.192}$$

Thus by constraint (5.87) and $B^{N1}_{1js} = \min\{A^{C}_{js} \cdot (1-L), U^{N1}_{1} = 400\}$, we obtain $f^{N1I}_{s} \leq \sum_{j \in N} \sum_{m \in M1} B^{N1}_{mjs} \cdot S^{N1}_{mj} = 160$. In other words, if a 1^{st} generation bio-refinery with capacity $U^{N1}_{2} = 400$ gets set up at a county with 160 Mgal/y corn production annually, it can handle the total internal flow, 160 $Mbu/$y.

Although given the concave function $C(k)$, solution number 2, setting up a bio-refinery with higher capacity should result in higher expected profit by taking advantage of economy of scale; solution number 1, setting up two bio-refineries with lower capacity, has higher internal flow which might generate more expected profit. In other words, the expected profit obtained from extra internal corn flow, which is converted to bioethanol, in solution number 1 may outweigh its extra set up cost, relative to solution number 2. ■

The following chapter is:

Ghahremanlou, D. and W. Kubiak (2020e). An approach to studying Sustainable Crude Oil Supply Chains (SCOSCs) evolved by changing US government policies - Part II (Case Study). *Journal of Cleaner Production*. **Submitted**.

Chapter 6

An approach to studying Sustainable Crude Oil Supply Chains (SCOSCs) evolved by changing US government policies - Part II (Case Study)

Abstract In order to study the Sustainable Crude Oil Supply Chains (SCOSCs) which evolve in response to change of Renewable Fuel Standard 2 (RFS2), Tax Credits for US and foreign bioethanol blended with gasoline (TCL and TCI respectively), Tariffs for US and foreign bioethanol blended with gasoline (TL and TI respectively), and Blend Wall (BW), we developed an algorithm, referred to as Extended Lean Model (ELM), in Part I, Ghahremanlou and Kubiak (2020a). In this Part II, we apply the model to real-life data for the State of Nebraska by solving $21,420$ alternative policy scenarios to optimality to investigate and compare SCOSCs created due to the changes in US government policies. The SCOSCs include the first and second generation bioethanol, their import and export, and the existing infrastructure in the State of Nebraska. The case study shows that the change

of RFS2 for the second generation bioethanol neither changes the expected profit of the investors nor increases the amount of bioethanol blended with gasoline and thus does not affect the SCOSC, however, the changes in tax credits and tariffs affect the SCOSC significantly. It further shows that tariffs for blending US and foreign bioethanol with gasoline must be at least 0.531 and 0.35 $\frac{\$}{\text{gal}}$ respectively to permit the government to shift the bioethanol production to meet demand for ethanol[2] as an ingredient for sanitizers used to prevent Coronavirus Disease (COVID-19). Finally, Part II provides a number of policy recommendations and directions for further research.

6.1 Introduction

Crude oil consumption is the main source of global warming, which is currently one of the most critical global issues (Wirth 1989b; Pearson 2011). Different countries have created policies towards reducing dependency on oil and its negative environmental impact (Sahebi et al. 2014a; Akgul et al. 2011). In this vein, the US, the biggest oil producer and consumer in the world (U.S. Energy Information Administration 2020b), has also created some policies, which are discussed by Ghahremanlou and Kubiak (2020a). These policies led the Conventional Crude Oil Supply Chain (CCOSC) to be merged with the Bioethanol Supply Chain (BSC) and create a Sustainable Crude Oil Supply Chain (SCOSC). The SCOSC has been recently hit twofold. First of all, the Oil War between Saudi Arabia and Russia resulted in the price of US oil becoming negative for the first time ever, and could result in the bankruptcy of many US oil companies (Egan and CNN Business 2020). The cheap price of oil reduced the market share for bioethanol, leading to bio-refineries closure. Secondly, the SCOSC has been crippled by Coronavirus Disease (COVID-19), as bioethanol

[2] Throughout this paper we reference ethanol as an ingredient in sanitizers, which require a higher grade of alcohol relative to bioethanol as a fuel additive.

currently produced is partially being directed to meet the unexpected need for ethanol to produce sanitizers (Voegele 2020a). The US government is involved to rescue the SCOSC from bankruptcy and improve the economy through its leverage of policies (Englund W. and Sheridan M. B. 2020; Weeks 2020). Keeping in mind the importance of these policies, this paper aims to investigate and compare SCOSCs, which evolve as the result of policy changes, from economic, environmental, and social points of view. Finally, we provide recommendations to both the government for leading the SCOSC, and investors for making robust strategic investment decisions.

A number of papers: Al-Qahtani et al. (2008), Wang et al. (2020), Carneiro et al. (2010), Yuan et al. (2019), Guyonnet et al. (2009), Iyer et al. (1998), and Tong et al. (2012) have been devoted to the CCOSC; please see Part I, Ghahremanlou and Kubiak (2020a) for a more comprehensive literature review. The BSC uses corn as the primary feedstock in the US (Baker and Zahniser 2007). The states of Nebraska and Iowa have maximum ethanol production in the US (Renewable Fuels Association 2010). The BSC and SCOSC in Iowa have been studied by You and Wang (2011), Li et al. (2015), Zhang and Hu (2013), Gebreslassie et al. (2012b), Li et al. (2014), Li and Hu (2014), Shah (2013) and Kazemzadeh and Hu (2015); however, only Kazemzadeh and Hu (2015) include government polices, RFS2 and TCL in their study. The policy impact on SCOSC in Nebraska was studied exclusively by Ghahremanlou and Kubiak (2020d), but the study did not consider harvesting sites for first generation bioethanol, existing first and second generation bio-refineries, new first generation bio-refineries, first generation bioethanol exporters, and first generation bioethanol importers from other states and abroad. We extend their study of the State of Nebraska in this paper by including those factors.

This paper is organized in five sections: Section 6.2, which explains the data used in this paper; Section 6.3 discusses the design of computational experiments; Section 6.4 reports on the results of the computational experiments from economic, environmental, and social point of view, while providing strategic and managerial insights and recommendations for the government and investors; Section 6.5 concludes our findings and provides directions for further research.

6.2 Case Study

6.2.1 Distance between counties

We have used ArcGIS 10.5 to find the direct distance between centers of $N = 93$ counties of Nebraska. The Nebraska Ethanol Board (2018) reports the locations of BRE1s, see Table 6.1. Also, there is a 2^{nd} generation bio-refinery, ABEGOA BIOENERGY, located in York county, Nebraska (Lux Research Inc. 2016).

6.2.2 Harvesting sites and feedstock

The corn production in each county is reported by the United States Department of Agriculture in bushels (U.S. Department of Agriculture 2012). Each bushel (*bu*) of corn is equal to 21.5 kg dry corn, and the corn mass to corn stover mass ratio is estimated 1:1 (Graham et al. 2007). Therefore, accordingly A^{C}_{js} and A^{CS}_{js} are reported for county j in Table 3.8.

6.2.3 Bio-refineries and Blending sites

The Nebraska Ethanol Board (2018) reports on capacity (in million bushels of corn per year or $Mbu/$y) and location of BRE1s, see Table 6.1. The county number for locations of BRE1s, $E1 = \{1, 6, 10, 22, 24, 30, 33, 40, 41, 44, 45, 50, 56, 59, 61, 62, 68, 70, 71, 78, 88, 89, 93\}$, is based on $N = \{1, 2, 3, ..., 93\}$, the potential locations of BRN1s, shown in Table 3.8. Each bushel (*bu*) of corn is equal to 21.5 kg dry corn (Graham et al. 2007). Therefore, accordingly we calculate the capacity for BRE1s, U_i^{E1}. Also, there is a 2^{nd} generation bio-refinery, ABEGOA BIOENERGY, located in Buffalo county, $E2 = \{10\}$, with capacity of $U^{E2} = 520,000\ \frac{MT}{y}$ corn stover (Lux Research Inc. 2016).

No.	County	Company Name	Capacity (Mbu/y)
1	Adams	E-Energy Adams	28
2	Boone	Valero Renewable Fuels	39
3	Holt	Green Plains Atkinson	17
4	Hamilton	Pacific Ethanol	16
5	Hamilton	Pacific Ethanol	37
6	Washington	Cargill	70
7	Morrill	Bridgeport Ethanol	18
8	Furnas	Nebraska Corn Processing	17
9	Merrick	Green Plains	36
10	Platte	ADM	195
11	Fillmore	Flint Hills Resources	42
12	Adams	Chief Ethanol Fuels	25
13	Dakota	Siouxland Ethanol	27
14	Dawson	Chief Ethanol Fuels	14
15	Perkins	Mid America Agri Products	18
16	Saunders	AltEn	10
17	Kearney	KAAPA Ethanol	28
18	Madison	Louis Dreyfus Commodities	18
19	Valley	Green Plains Renewable Energy	20
20	Pierce	Husker Ag	29
21	Buffalo	KAAPA Ethanol	31
22	Lincoln	Midwest Renewable Energy	9
23	Hitchcock	Trenton Agri Products	16
24	Hall	Green Plains	41
25	York	Green Plains	19

Table 6.1: Capacity and location of 1^{st} generation existing bio-refineries

The base cost for establishing a new 1^{st} generation bioethanol bio-refinery (dry mill bio-refinery) with base capacity $U_1^{N1} = 7,960\ \frac{MT}{y}$ is $C_1^{N1} = 1.25\ M\$$ (McAloon et al. 2000). We apply the following formula to estimate the costs for BRN1s (Wright and Brown 2007):

$$\text{cost-level}_k = k^{0.6}\text{base cost}. \tag{6.1}$$

We considered five different capacity levels for BRN1s. These are obtained by multiplying the base capacity by $k = 1, 5, 10, 20$ and 30 respectively. The multipliers are determined to provide a good fit with the distribution of corn for different scenarios. Consequently, the costs in million dollars for the capacities $U_1^{N1} = 7,960$, $U_2^{N1} = 39,800$, $U_3^{N1} = 79,600$, $U_4^{N1} = 159,200$, and $U_5^{N1} = 238,800$ (these were rounded for the computation) $\frac{MT}{\text{y}}$ of BRN1s are $C_1^{N1} = 1.25$, $C_2^{N1} = 3.28$, $C_3^{N1} = 4.98$, $C_4^{N1} = 7.54$, and $C_5^{N1} = 9.62$ respectively. The conversion factor for BRN1s, V^C is 125.6 $\frac{\text{gal}}{MT}$, since 21.5 kg corn generates 2.7 gal 1^{st} generation bioethanol (McAloon et al. 2000). We found $E^C = 63,197,468.35$ $\frac{\text{gal}}{\text{y}}$, by formula $(\text{total annual US corn - total annual Nebraska corn}) \cdot V^C$.

For the capacity of BRN2s, $U_1^{N2} = 772,151\frac{MT}{\text{y}}$, $U_2^{N2} = 1,544,303.78\frac{MT}{\text{y}}$, and $U_3^{N2} = 2,316,455.67\frac{MT}{\text{y}}$, and the costs are $C_1^{N2} = 422.5\ M\$$, $C_2^{N2} = 640.39\ M\$$, $C_3^{N2} = 816.77\ M\$$ (Ghahremanlou and Kubiak 2020d). Furthermore, regarding the capacity of BL, $H_1 = 36.59\frac{M\text{gal}}{\text{y}}$, $H_2 = 109.77\frac{M\text{gal}}{\text{y}}$, $H_3 = 182.95\frac{M\text{gal}}{\text{y}}$, $H_4 = 256.13\frac{M\text{gal}}{\text{y}}$, $H_5 = 329.31\frac{M\text{gal}}{\text{y}}$, and $H_6 = 402.49\frac{M\text{gal}}{\text{y}}$, the costs are $W_1 = 2.6\ M\$$, $W_2 = 5.03\ M\$$, $W_3 = 6.83\ M\$$, $W_4 = 8.36\ M\$$, $W_5 = 9.72\ M\$$, and $W_6 = 10.96\ M\$$. U_1^{N2} (Ghahremanlou and Kubiak 2020d); the C_1^{N2}, H_1 and W_1 are found in Humbird et al. (2011) and U.S. Environmental Protection Agency (1980) respectively; the other U_i^{N2}, C_i^{N2}, H_i, W_i are determined using formula 6.1. The loan for establishing BRN1s, BRN2s, and BLs is given with conditions, $B = 5.75$ billion dollars, $t = 30$ y, and $\Phi = 8\%$. The B is calculated from summation of set up costs for BRN2s, BLs, BRN1s which in billion dollars is 5, 0.25, and 0.5 respectively; 5 billion dollars cap to establish BRN2s as it was done in Kazemzadeh and Hu (2015) for the State of Iowa with higher than Nebraska bioethanol production; we then added 0.25 billion dollars cap to establish BLs (this amount is derived by considering amount of fuel demand in each county); 0.5 billion dollars for setting up BRN1s, by considering amount of corn available in each county. We found $E^{CS} = 39.75 \cdot 10^6 \ \frac{\text{gal}}{\text{y}}$, by formula (total annual US corn stover - total annual Nebraska corn stover) $\cdot V^{CS}$.

By Humbird et al. (2011), by investing $C_1^{N2} = 422.5\ M\$$ to establish a 2^{nd} generation bio-refinery of size U_1^{N2} one creates 60 jobs annually necessary to run that bio-refinery. Thus $J^{CSE} = \frac{60}{422.5 \cdot 10^6}$. By U.S. Environmental Protection Agency (1980), by investing $W_1 = 2.6$ $M\$$ to establish a blending site of size H_1 one creates 24 jobs annually necessary to run that blending site. Thus $J^B = \frac{24}{2.6 \cdot 10^6}$. Furthermore, Kim and Dale (2015) shows 6.48 full time construction jobs annually per million dollars in construction of bio-refinery are created. Thus $J^{Co} = 6.48$. The Nebraska Ethanol Board (2018) reports that $J^{CE} = \frac{1300}{5 \cdot 10^9}$, as 5 billion dollars investment on BRN1s in Nebraska has created 1,300 jobs annually.

6.2.4 Demand

By using data from U.S. Environmental Protection Agency (1980), we estimated the D_i fuel demand for each county of Nebraska, according to the formula 6.2. The detailed information is in Table 3.9.

$$D_i = \left(\frac{PC_i}{PN}\right) \cdot TG \tag{6.2}$$

where PC_i, PN, and TG are respectively population of county i, population of Nebraska, and total gasoline consumption in Nebraska.

6.2.5 Transportation

The cost for transportation of bioethanol and fuel includes distance-fixed cost and distance-variable cost, $C^{FTE} = 0.02\ \frac{\$}{\text{gal}}$ and $C^{VTE} = 16.2 \cdot 10^{-5}\ \frac{\$}{\text{gal} \cdot \text{mi}}$ respectively (the variable cost=1.3 $\frac{\$}{\text{mi} \cdot truckload}$ and truck capacity= $8,000$ gal) (Chen and Fan 2012). Likewise, the cost for transportation of corn stover includes distance-fixed cost and distance-variable cost $C^{FTCS} = 4.39\ \frac{\$}{MT}$ and $C^{VTCS} = 0 \cdot 19\ \frac{\$}{MT \cdot \text{mi}}$, respectively (Searcy et al. 2007). Similarly, $C^{FTC} = 6.46\ \frac{\$}{MT}$ and $C^{VTC} = 0.0015\ \frac{\$}{MT \cdot \text{mi}}$; these numbers derived by considering fixed cost \$6950, variable cost \$12809, 5.10^4 *bu*, and 8,000 mi (Iowa State University 2017). The jobs created for the transportation of corn stover $J^{TCS} = 1.35 \cdot 10^{-6}\ \frac{job}{MT \cdot \text{mi}}$ (Kim and Dale 2015). We assume $J^{TC} = J^{TCS}$ as they are produced on the farm, by same people, using same vehicles for transportation. The jobs created for transportation of bioethanol and fuel are almost $J^{TE} = 3.98 \cdot 10^{-9}$ and $J^{TEG} = 3.27 \cdot 10^{-9}$ respectively; we calculated these numbers by converting J^{TCS} to the appropriate unit using their density, given bioethanol density= 6.5 $\frac{\text{lb}}{\text{gal}}$ (Wight Hat Ltd. 2003a; CAMEO Chemicals. 2010), and fuel density= 6.073 $\frac{\text{lb}}{\text{gal}}$ (Wight Hat Ltd. 2003a; Wikimedia Foundation Inc. 2017).

6.2.6 Prices

The corn price in Nebraska is between 3.21 to 3.46 $\frac{\$}{bu}$ (Department of Agriculture, U.S. 2019). Therefore, we consider average of these prices as $P^C = 3.33\ \frac{\$}{bu} = 155\ \frac{\$}{MT}$, given 1 *bu* corn=21.5 kg (Graham et al. 2007). Also, the price of corn to bioethanol conversion, $C^{FEC} = 0.2\ \frac{\$}{\text{gal}}$ (McAloon et al. 2000). For the price of imported 1^{st} generation bioethanol from other countries, we considered average Brazil bioethanol price in the second week of May 2019, which priced between \$0.40 to \$0.50 per litre, $P^{FC} = 1.7\ \frac{\$}{\text{gal}}$, given 1 litre $= 0.264$ gal (Group and Press 1994), (Center for Advanced Studies on Applied Economics, University of São Paulo. 2019). Similarly, we considered average Iowa bioethanol price, min $= 1.41$ and max $= 1.69\ \frac{\$}{\text{gal}}$, as the imported 1^{st} generation bioethanol from other states, $P^{IC} = 1.55\ \frac{\$}{\text{gal}}$ (Agricultural Marketing Resource Center, U.S. 2019). For price of exported 1^{st} generation bioethanol, $P^{EC} = 1.43\ \frac{\$}{\text{gal}}$ was considered (McAloon et al. 2000). Furthermore, the price of the fuel produced by blending sites is set to $P = \$1.96$, which is the average price of E85 and gasoline during 2016 (E85 Prices 2016). There are three commercial cellulosic bioethanol in the US, ABEGOA BIOENERGY, DuPont and POET-DSM, which the cheapest price is for DuPont, $P^{ICS} = \$3.45$ (Lux Research Inc. 2016). By U.S. Environmental Protection Agency (2017d), the 1^{st} generation RINs price varies from 0.57 $\frac{\$}{RIN}$ to 0.9 $\frac{\$}{RIN}$ in 2016. Accordingly, we calculate the average price for 1^{st} generation RINs, $P^{RC} = 0.73\ \frac{\$}{RIN}$. Finally, the rest of the parameters values are given in Table 6.2.

6.2.7 Scenario generation

The uncertain parameters in this study are: feedstock availability (A_j^C and A_j^{CS}), feedstock price (P^C and P^{CS}), variable transportation costs (C^{VTC}, C^{VTCS}, C^{VTE} and C^{VTEG}), RIN prices (P^{RC} and P^{RCS}), bioethanol import prices (P^{IC}, P^{FC}, P^{ICS} and P^{FCS}), fuel price (P), gasoline price (P^G), bioethanol exporting prices (P^{EC} and P^{ECS}), number of jobs created (J^{Co}, J^{TC}, J^{TCS}, J^{TE}, J^{TEG}, J^{CE}, J^{CSE} and J^B) and fuel demand (D_i). We group the uncertain parameters based on their correlations, see Table 6.3, (Tong et al. 2013; Carneiro et al. 2010; Ghahremanlou and Kubiak 2020d). In the Technology evolution group, the uncertain parameters are J^{Co}, J^{TC}, J^{TCS}, J^{TE}, J^{TEG}, J^{CE}, J^{CSE} and J^B. The studies reveal that routine manual jobs and routine cognitive jobs have declined in the last few decades. Also, it is speculated that in the close future most of the jobs will be given to the machines to be done (The Economist. 2016; Ghahremanlou and Kubiak 2020d). In the Prices and Costs category, the uncertain parameters are P^C, P^{CS}, C^{VTC}, C^{VTCS}, C^{VTE}, C^{VTEG}, P^{RC}, P^{RCS}, P^{IC}, P^{FC}, P^{ICS}, P^{FCS}, P, P^G, P^{EC} and P^{ECS}. Gasoline and diesel (for transportation) are produced from crude oil, therefore their prices follow the same pattern (U.S. Energy Information Administration 2017b; Ghahremanlou and Kubiak 2020d). Furthermore, Wisner (2009) shows prices of feedstock, gasoline and bioethanol follow almost the same trend (Wisner 2009). Also, the price of any blend of ethanol and gasoline (fuel) follows the

Bio-refineries and blending sites - design		
Parameters	Amount (Unit)	References
B	$5.75 \cdot 10^9$ (\$)	Assumption
t	30 (y)	Kazemzadeh and Hu (2015)
ϕ	8%	Humbird et al. (2011) and Kazemzadeh and Hu (2015)
Q	30 (y)	Humbird et al. (2011)
Bio-refineries and blending sites - operation		
Parameters	Amount (Unit)	References
C^{FECS}	0.864 (\$/gal)	Humbird et al. (2011)
V	79 (gal/MT)	Humbird et al. (2011)
C^B	0.00327 (\$/gal)	U.S. Environmental Protection Agency (1980)
E^{CS}	$39.75 \cdot 10^6$ (gal/y)	U.S. Department of Agriculture (2012) and Humbird et al. (2011)
Unit prices		
Parameters	Amount (Unit)	References
P^{CS}	60 (\$/MT)	Klein-Marcuschamer et al. (2010)
P^{ECS}	2.15 (\$/gal)	Humbird et al. (2011)
P^G	2.085 (\$/gal)	AAA Gas Prices. (2017)
P^{RCS}	1.33 (\$/RIN)	U.S. Environmental Protection Agency (2016)
P^{FCS}	2.17 (\$/gal)	Tsanova (2016)
Harvesting Sites		
Parameters	Amount (Unit)	References
F	72%	Kazemzadeh and Hu (2015)
L	5%	Tong et al. (2013)
Transportation		
Parameters	Amount (Unit)	References
C^{FTCS}	4.39 (\$/MT)	Searcy et al. (2007)
C^{VTCS}	0.19 (\$/$MT \cdot$ mi)	Searcy et al. (2007)
C^{FTEG}	0.02 (\$/gal)	Chen and Fan (2012)
C^{VTEG}	$16.2 \cdot 10^{-5}$ (\$/gal · mi)	Chen and Fan (2012)
C^{FTE}	0.02 (\$/gal)	Chen and Fan (2012)
C^{VTE}	$16.2 \cdot 10^{-5}$ (\$/gal · mi)	Chen and Fan (2012)
τ	1.29	Kazemzadeh and Hu (2015)
Policies		
Parameters	Amount (Unit)	References
$\overline{R}$	10.1%	U.S. Environmental Protection Agency (2017b)
$\overline{\overline{R}}$	0.128%	U.S. Environmental Protection Agency (2017b)
T	0.45 (\$/gal)	Duffield et al. (2008)
$\overline{T}$	0.54 (\$/gal)	Duffield et al. (2008)

Table 6.2: Parameters information

prices of gasoline and bioethanol (Ghahremanlou and Kubiak 2020d). The price of RINs and bioethanol follow the same trend as bioethanol is sold with the attached RIN in the market (Ghahremanlou and Kubiak 2020d). Therefore, we conclude that all uncertain parameters in the category of Prices and Costs in Table 6.3 follow the same trend.

Group number	Group name	Uncertain parameters
1	Feedstock availability	1. Corn availability 2. Corn stover availability
2	Technology evolution	1. Number of jobs created $ spend on construction of bio-refineries and blending sites 2. Number of jobs created $MT \cdot$ mi corn transported 3. Number of jobs created $MT \cdot$ mi corn stover transported 4. Number of jobs created gal $\cdot$ mi of bioethanol transported 5. Number of jobs created $jobs \cdot$ gal $\cdot$ mi fuel blend transported 6. Number of jobs created by corn to bioethanol conversion operation 7. Number of jobs created by corn stover to bioethanol conversion operation 8. Number of jobs created by blending operation
3	Prices and Costs	1. Price of corn 2. Price of corn stover 3. Price of 1^{st} generation bioethanol RIN 4. Price of 2^{nd} generation bioethanol RIN 5. Price of 1^{st} generation bioethanol purchased from other states 6. Price of 1^{st} generation bioethanol purchased from other countries 7. Price of 2^{nd} generation bioethanol purchased from other states 8. Price of 2^{nd} generation bioethanol purchased from other countries 9. Price of fuel sold 10. Price of gasoline purchased 11. Price of 1^{st} generation bioethanol sold to the exporter 12. Price of 2^{nd} generation bioethanol sold to the exporter 13. Corn variable transportation cost 14. Corn stover variable transportation cost 15. Bioethanol variable transportation cost 16. Fuel variable transportation cost
4	Fuel demand	1. Fuel demand

Table 6.3: Uncertain parameters grouping

We discretize the space of uncertain parameters, by considering some scenarios ($s \in S$) for each uncertain parameter. Each scenario is a potential realization of an uncertain parameter. The scenarios are generated based on the average values of the parameters, historical data and estimation. We consider three scenarios for A_j^C and A_j^{CS}, namely, Base, High, and Low with probability 25%, 50%, and 25% respectively. For the Base scenario, we take the corn and corn stover production given in Table 3.8. In the High scenario we assume a 28% increase in the production and in the Low scenario we assume a 5% decrease in the production as compared to the Base scenario. The increase and decrease in the High and the Low scenarios, respectively, are the best and worst case corn production, respectively, observed in the U.S. from 2012 to 2017 (University of Nebraska. 2016). Likewise, for the technology evolution we also consider three scenarios: Base, High, and Low with probability 25%, 50%, and 25% respectively. In the Base scenario we use the values we mentioned in Section 6.2 for the eight uncertain parameters in the technology evolution group; for the High and the Low scenarios we assume 7% and 4% reduction respectively in those values due to automation and human resource dependency decline. Regarding the prices and costs, we consider two scenarios: High and Low with probability 50% and 50% respectively. In the High scenario the prices (1 – 12) and the costs (13 – 16) in this category increase by 10% and 1.5% respectively; while in the Low scenario the prices and the costs increase by 7% and 1% respectively (Tong et al. 2013). We consider two scenarios for fuel demand in counties of Nebraska: High and Low with probability 70% and 30% respectively. In the High scenario and Low scenario fuel demand increases 31% and decreases 15% respectively. These amounts are the maximum and minimum growth and decline of the fuel demand in Nebraska during 2006 to 2015, and their related probabilities are calculated based on the annual demand (Nebraska Department of Revenue 2017). All 36 possible scenarios and their probability (ω) distribution are given in Table 6.4.

Feedstock availability	Technology evolution	Prices and Costs	Fuel demand	Scenarios	Probability
	Base (25%)	High (50%)	High (70%)	1	0.021875
			Low (30%)	2	0.009375
		Low (50%)	High (70%)	3	0.021875
			Low (30%)	4	0.009375
Base (25%)	High (50%)	High (50%)	High (70%)	5	0.04375
			Low (30%)	6	0.01875
		Low (50%)	High (70%)	7	0.04375
			Low (30%)	8	0.01875
	Low (25%)	High (50%)	High (70%)	9	0.021875
			Low (30%)	10	0.009375
		Low (50%)	High (70%)	11	0.021875
			Low (30%)	12	0.009375
	Base (25%)	High (50%)	High (70%)	13	0.04375
			Low (30%)	14	0.01875
		Low (50%)	High (70%)	15	0.04375
			Low (30%)	16	0.01875
High (50%)	High (50%)	High (50%)	High (70%)	17	0.0875
			Low (30%)	18	0.0375
		Low (50%)	High (70%)	19	0.0875
			Low (30%)	20	0.0375
	Low (25%)	High (50%)	High (70%)	21	0.04375
			Low (30%)	22	0.01875
		Low (50%)	High (70%)	23	0.04375
			Low (30%)	24	0.01875
	Base (25%)	High (50%)	High (70%)	25	0.021875
			Low (30%)	26	0.009375
		Low (50%)	High (70%)	27	0.021875
			Low (30%)	28	0.009375
Low (25%)	High (50%)	High (50%)	High (70%)	29	0.04375
			Low (30%)	30	0.01875
		Low (50%)	High (70%)	31	0.04375
			Low (30%)	32	0.01875
	Low (25%)	High (50%)	High (70%)	33	0.021875
			Low (30%)	34	0.009375
		Low (50%)	High (70%)	35	0.021875
			Low (30%)	36	0.009375

Table 6.4: Scenarios

6.3 Design of Computational Experiments

This paper examine and compare SCOSCs created in response to changing government policies:

1. Tax credit for local bioethanol blended with gasoline ($TCL = \eta \cdot T$, $\forall \eta > 0$);

2. Tax credit for imported bioethanol from abroad blended with gasoline ($TCI = \theta \cdot \overline{T}$, $\forall \theta > 0$);

3. Tariff for local bioethanol blended with gasoline ($TL = \eta \cdot T$, $\forall \eta < 0$);

4. Tariff for imported bioethanol from abroad blended with gasoline ($TI = \theta \cdot \overline{T}$, $\forall \theta < 0$);

5. RFS2 mandate for 2^{nd} generation bioethanol ($\beta \cdot \overline{\overline{R}}$);

6. Blend wall (α).

Therefore, we explain what values are considered for each policy in this section.

The blend wall (α) can be 10%, 15% or 85% based on its definition. The cellulosic biofuel mandate determined in RFS2 for 2022 to 2016 are $\overline{\overline{R}}^{22} \cdot g^{22} = 16$ and $\overline{\overline{R}}^{16} \cdot g^{16} = 4.25$ billion gallons respectively (U.S. Environmental Protection Agency 2017c); where g^{22}, g^{16} are the gasoline consumption for 2022 and 2016. Thus, we obtain $\overline{\overline{R}}^{22} = (\frac{16}{4.25} \cdot \frac{g^{16}}{g^{22}}) \cdot \overline{\overline{R}}^{16}$. In order to obtain more comprehensive computational experiments, we find out the greatest $\overline{\overline{R}}^{22}$, as $\overline{\overline{R}}^{16} = \overline{\overline{R}} = 0.128\%$, by considering $g^{22} = g^{16}$. Since, $\beta \cdot \overline{\overline{R}}^{16} \leq \overline{\overline{R}}^{22}$, then $\beta \leq \frac{16}{4.25} \approx 3.76$. However, the government may reduce the mandate to 0, which would result in the lower bound, $0 \leq \beta$. Therefore, we consider $0 \leq \beta \leq 3.76$, and discretized it by taking $\beta = 0.3 \cdot k$, where $k = 0, 1, ..., 12$, and the value 3.76 is added to the discretized set.

According to Table 6.2, the Tax Credit for one gallon US bioethanol blended with gasoline is $T = \$0.45$. We assumed T would not exceed the price of one gallon of 1^{st} generation bioethanol produced in Nebraska, $P^{EC} = \$1.43$, since this would otherwise mean that the government would be paying for the bioethanol and provide it free to the blenders. Thus $T^2 = P^{EC} = \$1.43$, $\frac{T^2}{T} = \frac{1.43}{0.45} \approx 3.18$, which means T would increase up to 3.18. Therefore, $0 \leq \eta \leq 3.18$. Similarly we have considered the possibility of a Tariff for blending US bioethanol with gasoline, which would result in $-3.18 \leq \eta \leq 0$. Since, the equation (110) in Ghahremanlou and Kubiak (2020a)covers the Tax Credit and Tariff, we have $-3.18 \leq \eta \leq 3.18$. Likewise, for the foreign bioethanol blended with gasoline, $\frac{T^2}{T} = \frac{1.43}{0.54} \approx 2.65$. This would result in $-2.65 \leq \theta \leq 2.65$. The ranges created for η, $[-3.18, 3.18]$, and θ, $[-2.65, 2.65]$, are discretized by $\eta = -3.18 + 0.4 \cdot k$, where $k = 0, 1, ..., 15$ and $\theta = -2.65 + 0.4 \cdot k$, where $k = 0, 1, ..., 13$ respectively. The values, 3.18 and 2.65 are added to the discretized sets of η and θ respectively.

We ran the experiments to calculate $L_1(X_{\min})$ and $L_1(X_{\max})$ for all possible combinations of α, β, θ, and η. This results in $2 \cdot 3 \cdot 14 \cdot 15 \cdot 17 = 21,420$ different runs of the ELM. After that to determine $L_2(X_{\min})$ and $L_2(X_{\max})$ we plug $X_{\min}$ and $X_{\max}$ into L_2 for all possible combinations of α, β, θ, and η. The ELM consists of 1,224 continuous variables, 5,766 binary variables, and 3,309 constraints. The model is coded in Python 2.7 (Python Software Foundation 2001), and it is solved to optimality using Gurobi 7.0 (Gurobi Optimizer LLC. 2008). The experiments were performed on a Dell computer with an Intel Core i5-2400 3.10 GHz CPU and 8 GB RAM.

6.4 Analysis of Results, and Recommendations

This section examines SCOSCs created in response to changing US government policies, in four following subsections. We report on the economic, environmental, and social impact in the first three subsections. Finally, we explain the most robust strategic decisions in the last subsection.

The results presented in the four subsections are derived by solving the ELM, which includes two objective functions, L_1 the expected profit and L_2 the expected number of jobs. Since an investment is required to create the SCOSC, we consider L_1, as the highest priority, and solve it to the optimality. We approximate the distances, $\bar{d}$, $\bar{d}^{E1}$, and $\bar{d}^{E2}$, in L_1, by $\delta = \min_{i \neq j} d_{ij} > 0, i, j \in N$, $\gamma = \min_{i \neq j} d_{ij} > 0, i \in E1, j \in N$, and $\lambda = \min_{i \neq j} d_{ij} >$

$0, i \in E2, j \in N$ respectively, to obtain the optimal solution $X_{\min}$ for L_1, see Section 3.3 in Ghahremanlou and Kubiak (2020a). To obtain $X_{\max}$ for L_1 (see Section 3.3 in Ghahremanlou and Kubiak (2020a)), we approximate the distances, $\bar{d}$, $\bar{d}^{E1}$, and $\bar{d}^{E2}$, in L_1, by $\Delta = \max_{i \neq j} d_{ij} > 0, i, j \in N$, $\Gamma = \max_{i \neq j} d_{ij} > 0, i \in E1, j \in N$, and $\Lambda = \max_{i \neq j} d_{ij} > 0, i \in E2, j \in N$ respectively. From this point onward, $X_{\min}$ and $X_{\max}$ are called the best case and the worst case respectively, since by Observation 3 in Ghahremanlou and Kubiak (2020a) $L_1(X_{\min}) \geq L_1(X_{\max})$ and investors prefer to have maximum expected profit. To calculate L_2, we plug $X_{\min}$ and $X_{\max}$ into L_2, to obtain $L_2(X_{\min})$ and $L_2(X_{\max})$. This does not mean L_2 is solved to the optimality.

6.4.1 Economic Aspect

The primary objective of any private business investment in SCOSCs is maximizing the expected profit. However, government policies should motivate investment in Conventional Crude Oil Supply Chain, CCOSC, towards creating the SCOSCs; otherwise, for CCOSCs, complying with challenging policies might result in paralyzing the oil industry and related businesses. This is illustrated in 2018 bankruptcy of Philadelphia Energy Solutions, the largest U.S. East Coast oil refinery (DiNapoli and Renshaw 2018; Simeone 2018; Stein 2018). However, government tried to rescue the refinery by granting waivers (Kelly 2020). Recently we observe government's intervention towards boosting the economy, once again, during these incapacitating times created by the Oil War and COVID-19 (Englund W. and Sheridan M. B. 2020; Weeks 2020).

Figures 6.1 and 6.2 show the maximum expected profit L_1 in the best case, $L_1(X_{\min})$, and worst case, $L_1(X_{\max})$, respectively. The $L_1(X_{\min})$ and $L_1(X_{\max})$ are sensitive to α, θ, and η, and insensitive to β.

A side-by-side comparison of plots (a) and (b), (c) and (d), (e) and (f) reveals that when

β, denoted by the colorbar, increases (as back and front views show yellow color, which is the highest values of β), for any α, θ, and η, the expected profits $L_1(X_{\min})$ and $L_1(X_{\max})$ remains the same. The reason is the small coefficient of β, $\overline{\overline{R}} = 0.128\%$, see Table 6.2, in the equation (105) in Ghahremanlou and Kubiak (2020a).

One might think for any α, $L_1(X_{\min})$ and $L_1(X_{\max})$ are the same, and the transportation costs components, (120)-(128) of the objective function L_1 in Ghahremanlou and Kubiak (2020a) are redundant. The comparison of the two figures for any α (e.g., plots (a) in Figures 6.1 and 6.2 for $\alpha = 10\%$) demonstrates that $L_1(X_{\min})$ and $L_1(X_{\max})$ follow the same pattern though $L_1(X_{\min}) \geq L_1(X_{\max})$ for any α, β, θ, and η, which confirms Observation 3 in Ghahremanlou and Kubiak (2020a). To measure the numerical differences between $L_1(X_{\min})$ and $L_1(X_{\max})$ for each $\alpha = 10\%, 15\%$ and 85%, we define the maximum difference $MaxD^{\alpha} = \max_i\{L_1(X_{\min}(\alpha,i)) - L_1(X_{\max}(\alpha,i))\}$, the minimum difference $MinD^{\alpha} = \min_i\{L_1(X_{\min}(\alpha,i)) - L_1(X_{\max}(\alpha,i))\}$, and the average difference

$$AD^{\alpha} = \frac{\sum_{i=1}^{i=3570} [L_1(X_{\min}(\alpha,i)) - L_1(X_{\max}(\alpha,i))]}{3570}, \tag{6.3}$$

where the $X_{\min}(\alpha,i)$ and $X_{\max}(\alpha,i)$ are the optimal solutions for the best and the worst case respectively with $\alpha = 10\%, 15\%$ and 85%, and with the i-th combination of β, θ, and η for $i = 1,2,...,3570$; the 3570 in equation (6.3) is the number of combinations of β, θ, and η for any α, $14 \cdot 15 \cdot 17 = 3,570$, see Section 6.3. Consequently, we obtain the following in our experiments, which are in millions of dollars, $MaxD^{10\%} = 549.216$, $MaxD^{15\%} = 549.216$ and $MaxD^{85\%} = 549.216$; $MinD^{10\%} = 549.172$, $MinD^{\alpha=15\%} = 549.082$, and $MinD^{\alpha=85\%} = 547.826$; $AD^{10\%} = 549.195$, $AD^{15\%} = 549.152$, and $AD^{85\%} = 548.556$.

To illustrate the influence of changing α on $L_1(X_{\min})$ and $L_1(X_{\max})$, plots (g) in Figures 6.1 and 6.2 are drawn. The three plots in red, blue and green are respectively for $\alpha = 10\%$, 15% and 85% of the expected profit L_1 for fixed β, and variable η and θ. To better understand the difference between values of $L_1(X_{\min})$ for $\alpha = 10\%, 15\%$ and 85%, and the difference between values of $L_1(X_{\max})$ for $\alpha = 10\%, 15\%$ and 85%, for any β, θ and η, we compare them directly by defining

- $MaxP_1^{\alpha_1\alpha_2} = \max_i \{L_1(X_{\max}(\alpha_2, i)) - L_1(X_{\max}(\alpha_1, i))\}$: $MaxP_1^{10\%15\%} = 76.718$, $MaxP_1^{15\%85\%} = 1074.049$ in the experiments.

- $MaxP_2^{\alpha_1\alpha_2} = \max_i \{L_1(X_{\min}(\alpha_2, i)) - L_1(X_{\min}(\alpha_1, i))\}$: $MaxP_2^{10\%15\%} = 76.627$, $MaxP_2^{15\%85\%} = 1072.793$ in the experiments.

- $MinP_1^{\alpha_1\alpha_2} = \min_i \{L_1(X_{\max}(\alpha_2, i)) - L_1(X_{\max}(\alpha_1, i))\}$: $MinP_1^{10\%15\%} = 0$, $MinP_1^{15\%85\%} = 0$ in the experiments.

- $MinP_2^{\alpha_1\alpha_2} = \min_i \{L_1(X_{\min}(\alpha_2, i)) - L_1(X_{\min}(\alpha_1, i))\}$: $MinP_2^{10\%15\%} = 0$, $MinP_2^{15\%85\%} = 0$ in the experiments.

All the values in the bullet points above are in millions of dollars. We observe that whenever there is no bioethanol blended with gasoline, $B^\alpha = 0$, see Table 6.6, $MinP_1^{\alpha_1\alpha_2} = MinP_2^{\alpha_1\alpha_2} = 0$. Thus the increase of α results in the increase of L_1 whenever there is bioethanol blended with gasoline $B^\alpha \neq 0$, see Table 6.6; however, L_1 does not change if there is no bioethanol blended with gasoline, $B^\alpha = 0$, see Table 6.6. Also, we observe that the increase in α reduces the relative increment in L_1: $\frac{MaxP_1^{10\%15\%}}{15-10} = 15.3436$ and $\frac{MaxP_1^{15\%85\%}}{85-15} = 15.3435$, or $\frac{MaxP_2^{10\%15\%}}{15-10} = 15.3256$ and $\frac{MaxP_2^{15\%,85\%}}{85-15} = 15.3254$. We actually observe that a stronger condition holds, namely, for any $i = 1, 2, ..., 3570$, $P(10\%, 15\%, i) \geq P(15\%, 85\%, i)$, where $P(10\%, 15\%, i) = \frac{L_1(X_{\max}(15\%,i)) - L_1(X_{\max}(10\%,i))}{15-10}$ and $P(15\%, 85\%, i) = \frac{L_1(X_{\max}(85\%,i)) - L_1(X_{\max}(15\%,i))}{85-15}$. Similarly, $Q(10\%, 15\%, i) \geq Q(15\%, 85\%, i)$, for any $i = 1, 2, ..., 3570$, where $Q(10\%, 15\%, i) = \frac{L_1(X_{\min}(15\%,i)) - L_1(X_{\min}(10\%,i))}{15-10}$ and $Q(15\%, 85\%, i) = \frac{L_1(X_{\min}(85\%,i)) - L_1(X_{\min}(15\%,i))}{85-15}$.

Moreover, if US bioethanol is blended with gasoline, which happens if $(\eta, \theta) \in A$ where

$$A = A_1 \cup A_2 \cup A_3 \cup A_4 \cup A_5 \cup A_6 \cup A_7 \cup A_8 \tag{6.4}$$

and

- $A_1 = \{(\eta, \theta) | \eta = -0.78, \theta \in [-2.65, -0.25\}$
- $A_2 = \{(\eta, \theta) | \eta \in [-0.38, 0.02], \theta \in [-2.65, 0.15]\}$
- $A_3 = \{(\eta, \theta) | \eta = 0.42, \theta \in [-2.65, 0.55]\}$
- $A_4 = \{(\eta, \theta) | \eta = 0.82, \theta \in [-2.65, 0.95]\}$
- $A_5 = \{(\eta, \theta) | \eta = 1.22, \theta \in [-2.65, 1.35]\}$
- $A_6 = \{(\eta, \theta) | \eta = 1.62, \theta \in [-2.65, 1.75]\}$
- $A_7 = \{(\eta, \theta) | \eta \in [2.02, 2.42], \theta \in [-2.65, 2.15]\}$
- $A_8 = \{(\eta, \theta) | \eta \in [2.82, 3.18], \theta \in [-2.65, 2.65]\}$

for any α and β, with increasing η, $L_1(X_{\min})$ and $L_1(X_{\max})$ will increase. Likewise, when foreign bioethanol is blended with gasoline, where $(\eta, \theta) \in A'$,

$$A' = A'_1 \cup A'_2 \cup A'_3 \cup A'_4 \cup A'_5 \cup A'_6 \cup A'_7 \cup A'_8 \tag{6.5}$$

and

- $A'_1 = \{(\eta, \theta) | \eta \in [-3.18, -1.18], \theta \in [-0.25, 2.65]\}$
- $A'_2 = \{(\eta, \theta) | \eta = -0.78, \theta \in [0.15, 2.65]\}$
- $A'_3 = \{(\eta, \theta) | \eta \in [-0.38, 0.02], \theta \in [0.55, 2.65]\}$
- $A'_4 = \{(\eta, \theta) | \eta = 0.42, \theta \in [0.95, 2.65]\}$

- $A'_5 = \{(\eta, \theta) | \eta = 0.82, \theta \in [1.35, 2.65]\}$

- $A'_6 = \{(\eta, \theta) | \eta = 1.22, \theta \in [1.75, 2.65]\}$

- $A'_7 = \{(\eta, \theta) | \eta = 1.62, \theta \in [2.15, 2.65]\}$

- $A'_8 = \{(\eta, \theta) | \eta \in [2.02, 2.42], \theta \in [2.55, 2.65]\}$

for any α, β, $L_1(X_{\min})$ and $L_1(X_{\max})$ will increase.

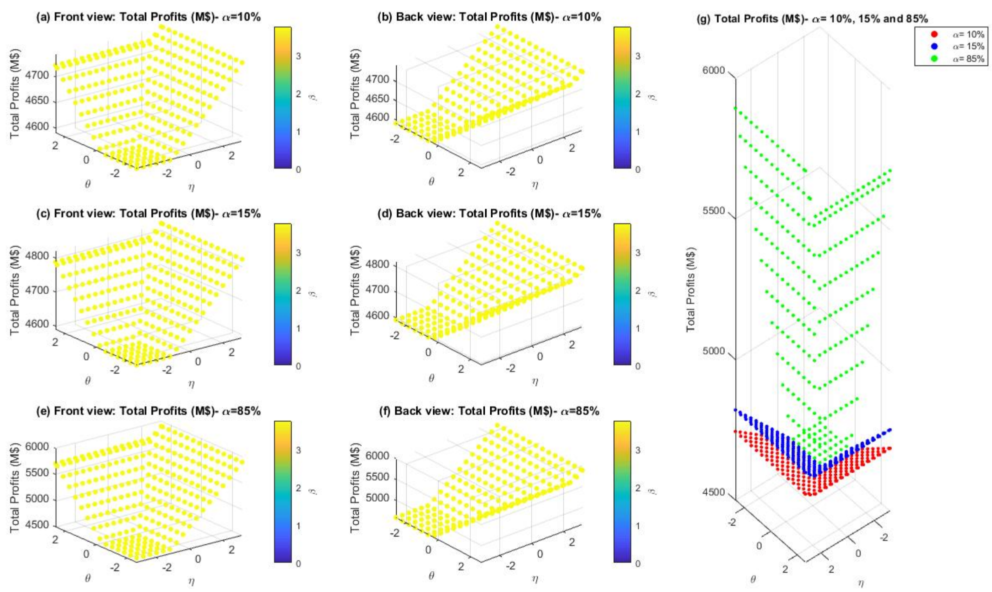


Figure 6.1: Expected profit for the best case, $L_1(X_{min})$, $\alpha = 10\%, 15\%$ and 85%

The investors expect their business to be always profitable, i.e. to find an optimal solution X, if any, such that $L_1(X) > 0$. On the other hand, the government attempts to utilize its budget by setting α, β, θ and η, while meeting its goals. For instance, the government may not provide the Tax Credits (TCs), by keeping $\theta = 0$ and $\eta = 0$, due to the allocation of funds, which might otherwise have been given as TCs to bioethanol and gasoline blenders

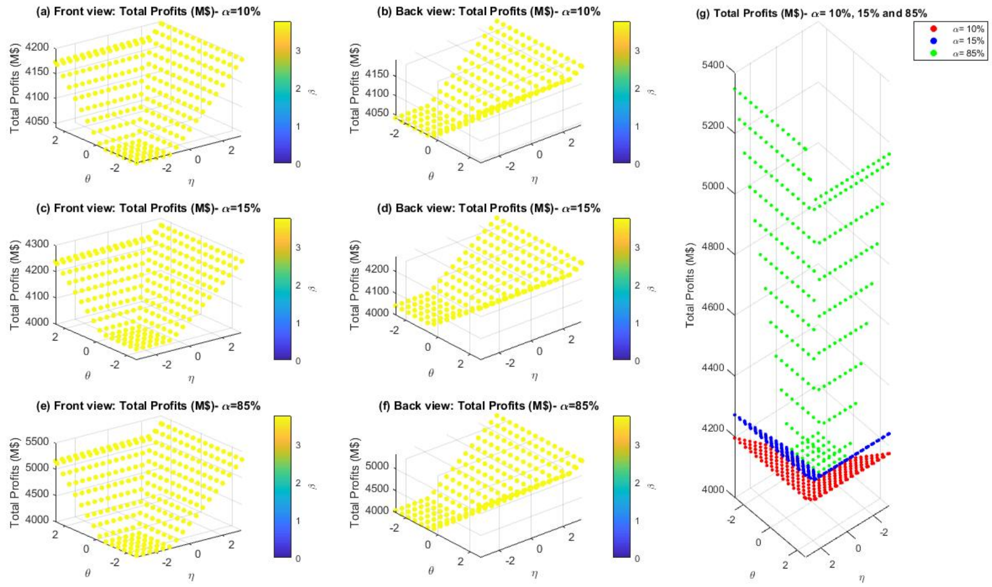


Figure 6.2: Expected profit for the worst case, $L_1(X_{max})$, $\alpha = 10\%, 15\%$ and 85%

in the budget, for other higher priority projects (Ghahremanlou and Kubiak 2020d). Although this might reduce the expected profit of the investment, it should not lead to an expected loss, $L_1 < 0$, or even worse to a bankruptcy, as this would not help the government to meet its goals, for example, creating more environmentally friendly fuels. Therefore, we define *Minimum* $\eta(\alpha, \beta, \theta)$ to be the minimum η, if any, such that $L_1(X_{\min}) > 0$ (or $L_1(X_{\max}) > 0$) for given α, θ, and β. The *Minimum* $\eta(\alpha, \beta, \theta) = -3.18$ for any α, θ and β. We observe that even if there is a tariff for blending US bioethanol and foreign bioethanol with gasoline, $\eta < 0$ and $\theta < 0$, the $L_1 > 0$. In other words, the government can generate income for itself by $TL = 3.18 \cdot 0.45 = 1.431$ and $TI = 2.65 \cdot 0.54 = 1.431$ dollar per gallon tariff respectively on blending US bioethanol and foreign bioethanol with gasoline, without providing any TC, which still results in positive expected profit for the investors in the SCOSC. However, we need to emphasize that this is for a collaborative SCOSC which we explained in Part I, Ghahremanlou and Kubiak (2020a), and might not always be the case.

6.4.2 Environmental Aspect

Emission reduction is one of the key reasons for the government to enact policies which result in creating the SCOSC. Clearly blending more bioethanol with gasoline is more environmentally friendly since it reduces the GHG. However, there is a recent increased need for ethanol as vital ingredient in sanitizers, suddenly in critical demand across the US and the world during the COVID-19 pandemic, diverting the production process of bioethanol used as a gasoline additive (Voegele 2020a). Exploration into the search for the best balance between ethanol and bioethanol production, respectively, for sanitizers and fuel is a direction for further research.

We define the average amount of 1^{st} and 2^{nd} generation bioethanol blended with gasoline over the 36 scenarios (see Table 6.4 for the definition of scenarios) for each computational experiment, i.e. quadruple α, β, θ and η, as follows

$$B^{\alpha} = \left(\frac{\sum_{s=1}^{36} \frac{e_s^{E1} + e_s^{E2} + e_s^{N1} + e_s^{N2} + h_s^{C} + h_s^{CS} + k_s^{C} + k_s^{CS}}{D_s}}{36} \right) \cdot 100. \tag{6.6}$$

The B^{α} is calculated for the best case, $X_{\min}$, and the worst case, $X_{\max}$, in our experiments. Table 6.5 reports the average B^{α} over all experiments. The average is not sensitive to β, as in the equation (105) the coefficient of β, $\overline{\overline{R}} = 0.128\%$, see Table 6.2, which is very small number, so this parameter is omitted from Table 6.5. However, both θ and η affect the average. The best case and the worst case have the same average B^{α}, for each α, so they are omitted from the table. We observe that for any α, B^{α} follows the same pattern, if $(\eta, \theta) \in A''$,

$$A'' = \{(\eta,\theta)|\eta \in [-3.18,-1.18], \theta \in [-2.65,-0.65]\} \tag{6.7}$$

the amount of $B^{\alpha} = 0$ otherwise, B^{α} achieves the BW. The BW would be a binding law, when $B^{\alpha} = \alpha$. In other words, if tariff for blending US and foreign bioethanol with gasoline to be at least $TL \geq 1.18 \cdot 0.45 = 0.531$ and $TI \geq 0.65 \cdot 0.54 = 0.35\ \frac{\$}{\text{gal}}$ respectively, no bioethanol is blended with gasoline, $B^{\alpha} = 0$. Where $B^{\alpha} = 0$, no bioethanol is blended with gasoline, although bioethanol is produced in Nebraska, see Tables 6.6 and 6.7, and sold to the exporters; this bioethanol could be upgraded and used to produce sanitizers to prevent the spread of Coronavirus Disease (COVID-19). For example, Green Plains bio-refinery, located in Nebraska, has provided ethanol for producing hand sanitizers (Voegele 2020a). One might ask what is the proportion of 1^{st} and 2^{nd} generation bioethanol in the fuel? The answer is, regardless of polices and best and worst cases, only 1^{st} generation bioethanol is blended with gasoline, while 2^{nd} generation bioethanol is not blended with gasoline at all. This might be due to considering the same amount of tax credit for 1^{st} and 2^{nd} generation bioethanol, see components (110) and (111) of the L_1 in Ghahremanlou and Kubiak (2020a), although the production cost of the former is lower than the latter, see Section 6.2.6. Thus, blending 1^{st} generation bioethanol with gasoline will result in higher expected profit.

<table>
<tr><td></td><td></td><td colspan="2">The worst case/The best case</td></tr>
<tr><td></td><td>$\alpha = 10\%, 15\%$</td><td colspan="2">η</td></tr>
<tr><td></td><td>$\alpha = 85\%$</td><td>$[-3.18,-1.18]$</td><td>$[-0.78,3.18]$</td></tr>
<tr><td rowspan="2">θ</td><td>$[-2.65,-0.65]$</td><td>$B^{\alpha} = 0\%$</td><td></td></tr>
<tr><td>$[-0.25,2.65]$</td><td colspan="2">$B^{\alpha} = \alpha$</td></tr>
</table>

Table 6.5: B^{α} for the best case and the worst case, $\alpha = 10\%, 15\%$ and 85%

6.4.3 Social Aspect

The government policies result in creation of the SCOSC which would generate jobs in construction, transportation, and operations. The number of jobs created, L_2, is a secondary objective function in our experiments thus $L_2(X_{\max})$ and $L_2(X_{\min})$ are calculated by plugging optimal solutions $X_{\max}$ and $X_{\min}$, to L_2 respectively. Therefore the values $L_2(X_{\max})$ and $L_2(X_{\min})$ are affected by the parameters α, β, θ, or η indirectly, since neither of them occurs in the definition of L_2. Tables 6.6, 6.7, 6.8, and 6.9 report the numbers r_m^{N1} of BRN1s established for each capacity $m \in M1$, the numbers r_m^{N2} of BRN2s established for each capacity $m \in M2$, the numbers b_n of BLs established for each capacity $n \in M3$, and the expected number L_2 of jobs created in Nebraska during a 30 year time frame set for the SCOSC.

The expected number L_2 of jobs created is insensitive to β, thus it is omitted from Table 6.9. For any α, in the worst case $L_2 = 1,168,645$ regardless of policies, as the SCOSC structure is the same, r_m^{N1}, r_m^{N2}, and b_n are not changed. However, in the best case:

- $L_2 = 618,561$, where no bioethanol or only foreign bioethanol is blended with gasoline, $(\eta, \theta) \in A' \cup A''$, (see equations (6.5) and (6.7)), as the SCOSC structure is the same, r_m^{N1}, r_m^{N2}, and b_n are not changed;
- L_2 increases by increasing α, where only US bioethanol is blended with gasoline, $(\eta, \theta) \in A$ (see equation (6.4)), as the number of blending sites will increase; these blending sites blend the bioethanol produced by bio-refineries located in Nebraska, with gasoline.

To obtain a positive expected profit, highest social effect, and the most environmentally friendly fuel, we recommend that the government considers the tax credits and tariffs such that $(\eta, \theta) \in A$ (see equation (6.4)). This leads to Nebraska's total bioethanol independence, meaning no need for foreign bioethanol to be imported to this state. This may also result in revenue generation for the US government. For example, to gain these advantages, the maximum tariff for US bioethanol blended with gasoline must be $TL \leq 0.78 \cdot T = 0.78 \cdot 0.45 = 0.35\ \frac{\$}{\text{gal}}$ (or $TCL > 0$) and the tariff for foreign bioethanol must be at least $TI \geq 0.25 \cdot \overline{T} = 0.25 \cdot 0.54 = 0.135\ \frac{\$}{\text{gal}}$. Moreover, $TL \leq 0.35\ \frac{\$}{\text{gal}}$ and $TI \geq 0.135\ \frac{\$}{\text{gal}}$ create the most robust SCOSC. Note, the most environmentally friendly fuel is the one in which the amount of 2^{nd} generation bioethanol blended with gasoline reaches the BW, α, since 2^{nd} generation bioethanol has the maximum GHG emission reduction. However, what we refer to as the most environmentally friendly fuel in this paper is a fuel which consists of a maximum amount of 1^{st} generation bioethanol permitted by the BW and gasoline.

	The worst case		The best case	
	$\alpha = 10\%$	$\alpha = 15\%$	$\alpha = 10\%$	$\alpha = 15\%$
r_1^{N1}	0	0	0	0
r_2^{N1}	0	0	0	0
r_3^{N1}	1	1	1	1
r_4^{N1}	0	0	0	0
r_5^{N1}	56	56	56	56
r_1^{N2}	0	0	0	0
r_2^{N2}	0	0	1	1
r_3^{N2}	0	0	3	3
b_1	48	48	0	0
b_2	1	1	1	1
b_3	1	1	0	0
b_4	0	0	0	0
b_5	1	1	0	0
b_6	0	0	2	2

Table 6.6: Strategic decisions for the worst case and the best case, $\alpha = 10\%$ and 15%

6.4.4 Further Strategic and Managerial Insights

The government is using its policy leverage to manage the emergency situation created by the Oil War and COVID-19 (Englund W. and Sheridan M. B. 2020; Weeks 2020). How-

	$\alpha = 85\%$	
	The worst case	The best case
r_1^{N1}	0	0
r_2^{N1}	0	0
r_3^{N1}	1	1
r_4^{N1}	0	0
r_5^{N1}	56	56
r_1^{N2}	0	0
r_2^{N2}	0	1
r_3^{N2}	0	3

Table 6.7: Number of bio-refineries for the worst case and the best case, $\alpha = 85\%$

	$\alpha = 85\%$	
	The worst case	The best case
b_1	48	$\begin{cases} 0 & if \quad (\eta,\theta) \in A' \cup A'' \text{ (see equations (6.5) and (6.7))} \\ 6 & if \quad otherwise \end{cases}$
b_2	1	1
b_3	1	$\begin{cases} 0 & if \quad (\eta,\theta) \in A' \cup A'' \text{ (see equations (6.5) and (6.7))} \\ 1 & if \quad otherwise \end{cases}$
b_4	0	0
b_5	1	0
b_6	0	$\begin{cases} 2 & if \quad (\eta,\theta) \in A' \cup A'' \text{ (see equations (6.5) and (6.7))} \\ 1 & if \quad otherwise \end{cases}$

Table 6.8: Number of blending sites for the worst case and the best case, $\alpha = 85\%$

The worst case	$\alpha = 10\%$	$L_2 = 1168645$
	$\alpha = 15\%$	$L_2 = 1168645$
	$\alpha = 85\%$	$L_2 = 1168645$
The best case	$\alpha = 10\%$	$\begin{cases} L_2 = 618561 & if \quad (\eta,\theta) \in A' \cup A'' \text{ (see equations (6.5) and (6.7))} \\ L_2 = 618654 & if \quad otherwise \end{cases}$
	$\alpha = 15\%$	$\begin{cases} L_2 = 618561 & if \quad (\eta,\theta) \in A' \cup A'' \text{ (see equations (6.5) and (6.7))} \\ L_2 = 618779 & if \quad otherwise \end{cases}$
	$\alpha = 85\%$	$\begin{cases} L_2 = 618561 & if \quad (\eta,\theta) \in A' \cup A'' \text{ (see equations (6.5) and (6.7))} \\ L_2 = 710063 & if \quad otherwise \end{cases}$

Table 6.9: Number of jobs for the worst case and the best case, $\alpha = 10\%$, 85% and 15%

ever, the policies may not be fully advantageous to the SCOSCs in the complex business market, see 2018 Philadelphia Energy Solutions bankruptcy (DiNapoli and Renshaw 2018; Simeone 2018; Stein 2018). Therefore, to find the most robust strategic decisions which are insensitive to policies and transportation costs we compare the results of Tables 6.6, 6.7, and 6.8 explained in detail in Sections 6.4.4.1 and 6.4.4.2. In short, we recommend the following most robust strategic decisions to the investors, establishing:

- a 1^{st} generation bioethanol bio-refinery at Douglas county with capacity U_3^{N1};
- 56 1^{st} generation bioethanol bio-refineries with capacity U_5^{N1}, located in counties $j \in BRL = \{Adams, Antelope, Boone, Box\ Butte, Buffalo, Burt, Butler, Cass, Cedar, Chase, Clay, Colfax, Cuming, Custer, Dawson, Dodge, Dundy, Fillmore, Franklin, Furnas, Gage, Gosper, Greeley, Hall, Hamilton, Harlan, Holt, Howard, Jefferson, Kearney, Keith, Knox, Lancaster, Lincoln, Madison, Merrick, Morrill, Nuckollas, Otoe, Perkins, Phelps, Pierce, Plantte, Polk, Richardson, Saline, Saunders, Scotts\ Bluff, Seward, Sherman, Thayer, Valley, Washington, Wayne, Webster, York\}$, which are the highest corn production counties, see Table 3.8;
- a blending site with capacity H_2 located in Sarpy county;
- a blending site with capacity H_6 located in Douglas county.

Furthermore, our computations show that bioethanol production by these bio-refineries takes place regardless of any policy; where bioethanol is not blended with gasoline, $B^{\alpha} = 0$, see Table 6.5, their production is sold to the exporters, see constraints (64) and (66) in Ghahremanlou and Kubiak (2020a). However, when polices encourage blending more US bioethanol with gasoline, by increasing η, see Table 6.5, their bioethanol production is blended with gasoline.

6.4.4.1 For $\alpha = 10\%$ and 15%

Table 6.6 display r_m^{N1}, r_m^{N2}, and b_n for $\alpha = 10\%$ and 15%. The r_m^{N1}, r_m^{N2}, and b_n are insensitive to β, η and θ, thus these are omitted from the table. It is worth mentioning that there are existing bio-refineries, r_m^{N1} and r_m^{N2}, see Appendix 6.2.3. Comparing the best and worst cases results in the following case independent insights:

- *Bio-refineries.* Douglas county is the most robust location for setting up a 1^{st} generation bioethanol bio-refinery with capacity U_3^{N1}. Also, 56 of 1^{st} generation bioethanol bio-refineries with capacity U_5^{N1}, located in $j \in BRL$, see Section 6.4.4, are robust too.

- *Blending sites.* The most robust location for a blending site with capacity H_2 is Sarpy county.

- *Other insights.* The number of 1^{st} generation bioethanol bio-refineries are the same in the best and worst cases, and are also insensitive to policies. The number of 2^{nd} generation bioethanol bio-refineries in the best case is $11 \cdot U_1^{N2}$, more than the number of 2^{nd} generation bio-refineries in the worst case, which is zero. This shows the importance of corn stover transportation cost, which is due to the low density of corn stover. The number of blending sites, in the worst case, is more than the number of blending sites in the best case. This indicates the importance of the bioethanol and fuel transportation costs. Also, in the worst case, the total capacity of blending sites is $65 \cdot H_1$, while in the best case the total capacity of blending sites is $25 \cdot H_1$. This shows that although $25 \cdot H_1$ capacity of the blending site is enough for meeting the fuel demand, there is a need for $65 \cdot H_1$ capacity of the blending site, in the worst case. This implies that some of the available capacity of blending sites is not used, in the worst case. To obtain a positive expected profit, highest social effect, and the most environmentally friendly fuel, we recommend that the government considers the tax credits and tariffs such a that $(\eta,\theta) \in A$ (see equation (6.4)). This leads to Nebraska's total bioethanol independence, meaning no need for foreign bioethanol to be imported to this state. Also, the US government may generate income for itself. For example, to gain these advantages, the maximum tariff for US bioethanol blended with gasoline must be $TL \leq 0.78 \cdot T = 0.78 \cdot 0.45 = 0.35 \frac{\$}{\text{gal}}$ (or $TCL > 0$) and the tariff for foreign bioethanol must be at least $TI \geq 0.25 \cdot \overline{T} = 0.25 \cdot 0.54 = 0.135 \frac{\$}{\text{gal}}$.

6.4.4.2 For $\alpha = 85\%$

Tables 6.7, and 6.8 display r_m^{N1}, r_m^{N2}, and b_n for $\alpha = 85\%$. The r_m^{N1} and r_m^{N2} are insensitive to β, η and θ, so these are omitted from the tables. However, b_n is only independent to β, which is deleted from the Table 6.8. It is worth mentioning that there are existing bio-refineries, r_m^{N1} and r_m^{N2}, see Appendix 6.2.3. Comparing the best and worst cases results in the following case independent insights:

- *Bio-refineries.* Douglas county is the most robust location for setting up a 1^{st} generation bio-refinery with capacity U_3^{N1}. Also, 56 of 1^{st} generation bio-refineries with capacity U_5^{N1}, located in $j \in BRL$, see Section 6.4.4, are robust too.
- *Blending sites.* The most robust location for a blending site with capacity H_2 is Sarpy county.
- *Other insights.* For $\alpha = 85\%$, the r_m^{N1} is the same in the worst and best case. The number of 2^{nd} generation bio-refineries in the best case is $11 \cdot U_1^{N2}$, more than the number of 2^{nd} generation bio-refineries in the worst case, which is zero. This shows the importance of corn stover transportation cost, which is due to the low density of corn stover. The number of blending sites, in the worst case, is more than the number

of blending sites in the best case. This indicates the importance of the bioethanol and fuel transportation costs. Also, in the worst case, the total capacity of blending sites is $65 \cdot H_1$, while in the best case the total capacity of blending sites is $25 \cdot H_1$. This shows that although $25 \cdot H_1$ capacity of the blending site is enough for meeting the fuel demand, there is a need for $65 \cdot H_1$ capacity of the blending site, in the worst case. This implies that some of the available capacity of blending sites is not used, in the worst case. Furthermore, although the total capacity of the blending site is $25 \cdot H_1$, in the best case, when only US bioethanol is blended with gasoline, the number of blending sites is more than the number of blending sites when only foreign bioethanol is blended with gasoline. To obtain a positive expected profit, highest social effect, and the most environmentally friendly fuel, we recommend that the government considers the tax credits and tariffs such a that $(\eta, \theta) \in A$ (see equation (6.4)). This leads to Nebraska's total bioethanol independence, meaning no need for foreign bioethanol to be imported to this state. Also, the US government may generate income for itself. For example, to gain these advantages, the maximum tariff for US bioethanol blended with gasoline must be $TL \leq 0.78 \cdot T = 0.78 \cdot 0.45 = 0.35 \ \frac{\$}{\text{gal}}$ (or $TCL > 0$) and the tariff for foreign bioethanol must be at least $TI \geq 0.25 \cdot \overline{T} = 0.25 \cdot 0.54 = 0.135 \ \frac{\$}{\text{gal}}$.

6.5 Conclusions and Further Research

We studied Sustainable Crude Oil Supply Chains (SCOSCs) evolved by changing the US government policies: Renewable Fuel Standard 2 (RFS2), Tax Credits for US and foreign bioethanol blended with gasoline (TCL and TCI respectively), Tariffs for US and foreign bioethanol blended with gasoline (TL and TI respectively), and Blend Wall (BW). The study included first and second generation bioethanol, their import and export, and all the existing infrastructures, in Nebraska. We employed the Extended Lean Model (ELM) developed by Ghahremanlou and Kubiak (2020a). We conclude:

- If $TL \leq 0.78 \cdot 0.45 = 0.351 \ \frac{\$}{\text{gal}}$ or $TI \leq 0.25 \cdot 0.54 = 0.135 \ \frac{\$}{\text{gal}}$, then bioethanol is always blended with gasoline. Under these conditions an increase in the BW (α) for fixed β, η, and θ: (1) increases the expected annual profit of the SCOSC, however, this increment is declining as α grows; (2) results in production of more environmentally friendly fuel; (3) keeps the expected number of jobs created steady or growing by keeping the numbers of bio-refineries and blending sites as well as their capacities steady or growing. Therefore, a strategy to increase the BW to 85% by, for instance, having only Flex-Fuel Vehicles registered emerges as a promising direction for the US government to pursue.

- For fixed α, η, and θ, increasing RFS2 by increasing β: (1) does not affect the expected profit as the mandate for second generation bioethanol is insignificant; (2) does not affect the amount of bioethanol blended with gasoline; and (3) does not affect the expected number of jobs created, and the number of bio-refineries and blending sites, and their capacities.

- If US bioethanol is blended with gasoline, assuming other policies are fixed, then increasing TCL by increasing $\eta \geq 0$: (1) increases the expected annual profit; (2) provides incentives to produce the most environmentally friendly blend, and to attain the highest number of jobs created under the policies by increasing the amount of US bioethanol blended with gasoline.

- If US bioethanol is blended with gasoline, assuming other policies are fixed, then increasing TL by decreasing $\eta \leq 0$ decreases the annual expected profit while the amount of bioethanol blended with gasoline and number of expected jobs stay the same. We observe that $TL = 1.18 \cdot 0.45 = 0.531 \ \frac{\$}{\text{gal}}$ or higher stops blending the

US produced bioethanol with gasoline. Therefore, if the government wants to replace cellulosic bioethanol by other renewable transportation fuels, e.g., solar, it may consider $TL \geq 1.18 \cdot 0.45 = 0.531 \ \frac{\$}{\text{gal}}$.

- Finally, if foreign bioethanol is blended with gasoline, assuming other policies are fixed, then increasing TCI by increasing $\theta \geq 0$: (1) increases the expected annual profit; (2) does not affect the amount of bioethanol blended with gasoline since the blend wall is then binding; (3) does not influence the number of expected jobs created in Nebraska. In contrast, if foreign bioethanol is blended with gasoline, assuming other policies are fixed, then increasing TI by decreasing $\theta \leq 0$ reduces the expected annual profit, although it does not reduce the environmental friendliness of the blend, and it does not affect the number of jobs created.

To summarize, the government should be very careful while changing TCL, TCI, TL and TI, since obtaining more environmentally friendly fuel may result in foreign bioethanol dependency. To obtain a positive annual expected profit, highest social effect, and the most environmentally friendly fuel, the US government can consider the maximum tariff for US bioethanol blended with gasoline to be $TL \leq 0.78 \cdot T = 0.78 \cdot 0.45 = 0.35 \ \frac{\$}{\text{gal}}$ (or $TCL > 0$) and the minimum tariff for foreign bioethanol to be $TI \geq 0.25 \cdot \overline{T} = 0.25 \cdot 0.54 = 0.135 \ \frac{\$}{\text{gal}}$. This makes Nebraska totally independent from foreign bioethanol importation, as well as conceivably generating some income for the government. Moreover, $TL \leq 0.35 \ \frac{\$}{\text{gal}}$ and $TI \geq 0.135 \ \frac{\$}{\text{gal}}$ create the most robust SCOSC.

Although the government is using policy leverage to grapple with the crisis situation brought about by the Oil War and COVID-19 (Englund W. and Sheridan M. B. 2020; Weeks 2020), this may not be totally beneficial to the SCOSCs in this complicated business market, see 2018 Philadelphia Energy Solutions bankruptcy (DiNapoli and Renshaw 2018; Simeone 2018; Stein 2018). Therefore, we recommend the following robust decisions, insensitive to policy changes. The investors should establish a 1^{st} generation bio-refinery at Douglas county with capacity U_3^{N1}. Also, 56 of 1^{st} generation bio-refineries with capacity U_5^{N1}, located in Adams, Antelope, Boone, Box Butte, Buffalo, Burt, Butler, Cass, Cedar, Chase, Clay, Colfax, Cuming, Custer, Dawson, Dodge, Dundy, Fillmore, Franklin, Furnas, Gage, Gosper, Greeley, Hall, Hamilton, Harlan, Holt, Howard, Jefferson, Kearney, Keith, Knox, Lancaster, Lincoln, Madison, Merrick, Morrill, Nuckollas, Otoe, Perkins, Phelps, Pierce, Plantte, Polk, Richardson, Saline, Saunders, Scotts Bluff, Seward, Sherman, Thayer, Valley, Washington, Wayne, Webster, and York counties, which are the highest corn producing counties. A blending site with capacity H_2 should be located in Sarpy county. A blending site with capacity H_6 should be located in Douglas county.

If the government wants to shift the focus for bioethanol production, for instance, to producing sanitizers to prevent the spread of Coronavirus Disease (COVID-19), tariffs for blending US and foreign bioethanol with gasoline must be at least 0.531 and 0.35 $\frac{\$}{\text{gal}}$ respectively. These tariffs are leading bio-refineries to help in the prevention of COVID-19, otherwise only several bio-refineries out of 198 in total provide bioethanol for producing sanitizers U.S. Energy Information Administration (2020a) .

Travel restrictions ensuing from the current COVID-19 pandemic resulted in a drop in the demand for gasoline. This drop along with the Oil War caused a depression in the demand for bioethanol, which in turn resulted in the shut down of some bio-refineries. On the other hand, however, the demand for ethanol required to produce sanitizers to help prevent COVID-19 from spreading has increased. The drop and the increase may counterbalance to some degree. In order to better understand how to change the policies that meet the demand for sanitizers while meeting demand for environmentally friendly fuel, we propose, as a direction for further study, extending our model in Ghahremanlou and Kubiak (2020a) by including sanitizer producers as a part of the supply chain. The research would also shed light on whether the demand increase for ethanol[2], as a component for sanitizers, could balance the demand decrease for bioethanol, as fuel additive, to create a more stable demand. This more stable demand might save bio-refineries from closure by generating higher expected profit due to a hike in the price of ethanol because of its requirement as an ingredient in sanitizers in the fight of COVID-19 pandemic Wallace (2020) .

The Extended Lean Model (ELM) developed by Ghahremanlou and Kubiak (2020a) applies to any state of the US which has already existing infrastructures in place, and with a little modification, can be used for all the states. Therefore, studying SCOSCs created in other states in response to changing government policies is a new research direction. Furthermore, the model can be employed in yet another unexplored research direction by easily adopting it to other countries with different policies for dealing with global warming and energy security, and different primary types of feedstock used for bioethanol production.

[2]Throughout this paper we reference ethanol as an ingredient in sanitizers, which require a higher grade of alcohol relative to bioethanol as a fuel additive.

The following chapter is:

Ghahremanlou, D. and W. Kubiak (2020f). US Sustainable Crude Oil Supply Chains (SCOSCs) during economic crises. To be submitted.

Chapter 7

US Sustainable Crude Oil Supply Chains (SCOSCs) during economic crises

Abstract Recently US oil and bioethanol industries have faced drastic economic damage due to Coronavirus Disease (COVID-19) and the 2020 Saudi Arabia-Russia Oil Price War, resulting in many bankruptcies. Government policies have brought these two main industries together to ensure Sustainable Crude Oil Supply Chains (SCOSCs), to combat global warming and energy insecurity. This motivated us to extend the risk neutral study of Ghahremanlou and Kubiak (2020a) to protect the current and new SCOSCs against financial risks during economic crises by providing insights for the government and the investors, working to rescue the industries. Following suit, we employ Conditional Value-at-Risk (CVaR), a risk averse approach, and develop a two-stage stochastic programming model. We consider Renewable Fuel Standard 2 (RFS2), Tax Credits for US and foreign bioethanol blended with gasoline (TCL and TCI respectively), Tariffs for US and foreign bioethanol blended with gasoline (TL and TI respectively), and Blend Wall (BW) as the government policy leverages for helping the SCOSC. We perform a case study of the State of Nebraska by carrying out a computational experiment with 10,710 different policy sce-

narios to provide insights for the government about the leading power of the policy leverages. We provide several recommendations to the government in this paper, for example, imposing at least 0.171 and 0.205 $\frac{\$}{\text{gal}}$ tariffs for US and foreign bioethanol blended with gasoline the bio-refineries output may be led towards producing ethanol[2] used in production of sanitizers for preventing the spread of COVID-19. Additionally, we recommend robust strategic investment decisions to businesses during policy changes within economic crises. We also uncover strategic investment decisions resilient to economic crises.

Keywords: Conditional Value-at-Risk, Sustainable Crude Oil Supply Chain, Two-Stage Stochastic Programming, Government Policies

7.1 Introduction

Global transportation fuel demand has recently plummeted due to self isolation resulting from COVID-19 and the 2020 Saudi Arabia-Russia Oil Price War. This drop is approximated to be about 60% by end of May 2020 (Tagliapietra 2020). Some oil and bioethanol companies have already filed bankruptcy in the US, the biggest oil and bioethanol producer in the world. For examples, see Whiting Petroleum Corp, the biggest oil producer in North Dakota's Bakken region (Nair 2020), Unit Corp (Taylor 2020), and Diamondback Industries (Posgate 2020); the number of bankruptcies is predicted to be over 1,100 companies (Egan and CNN Business 2020). Similarly, this has led to the shutdown of more than 70 bio-refineries (Neeley 2020). For instance, see One Earth Energy (Voegele 2020b) and Element (The Andersons Inc. 2020). Government policies and supply chain decisions of investors are trying to rescue the SCOSC, which in 2015 has contributed 7.6% of US Gross Domestic Product (GDP) and 5.6% of total US employment (Iaccino 2019). With the aim

[2]We reference ethanol as an ingredient in sanitizers, which require a higher grade of alcohol relative to bioethanol as a fuel additive.

of assisting government and investors, the goal of this paper is to study both the leading role of the policies and the SCOSC decisions that are beneficial and resilient during economic crises.

Over the last five decades new US policies resulted in the creation of the Bioethanol Supply Chain (BSC) and joining it with the Conventional Crude Oil Supply Chain (CCOSC), forming the SCOSC, in order to reduce greenhouse-gas (GHG) emissions and enhance energy independence (Ghahremanlou and Kubiak 2020c;d). The CCOSC has faced some crises during its history, e.g., the 1970s oil crises, but it is still recognized as the underling reason for making the US a world power (Smith 2009; Painter 2012). Assis et al. (2019); Zhou et al. (2020); Yuan et al. (2020) are among the recent studies focusing on the CCOSC, although there has been a great deal of research on different oil streams, for the recent ones see Jia et al. (2020); Hu et al. (2020); Yue et al. (2020); Al-Rbeawi (2020); Zuo et al. (2020). On the other hand, the BSC was born by government policies due to its economic, environmental, and social advantages (Dutton 1971; Ghahremanlou and Kubiak 2020d). Its benefits attracted many researchers, for example, see Ahranjani et al. (2020); Lan et al. (2020); Akbarian-Saravi et al. (2020). The US Environmental Protection Agency permits usage of bioethanol as an additive to gasoline due to technological issues (Agarwal 2007; Yacobucci 2010). This means bioethanol and gasoline are blended in their down stream to produce fuel; this fuel supply chain is called the SCOSC.

The policies impacting the SCOSC can be divided into three main categories: regulatory, incentive, and deterrent. This paper covers all these categories, by considering Renewable Fuel Standard 2, Blend Wall, Tax Credits, and Tariffs. To ensure a market for bioethanol, Renewable Fuel Standard 2 (RFS2) came into existence by the 2007 Energy Independence and Security Act (EISA) (McPhail et al. 2011). To comply with RFS2, all refineries and gasoline importers, called obligated parties, need to blend a minimum amount of bioethanol, e.g., 1^{st} and 2^{nd} generation bioethanol, with their gasoline before distributing on the market (Cornell Law School 2010); this amount is called mandate or Renewable Volume Obligation (RVO) (Thompson et al. 2009). The maximum percentage of fuel additive bioethanol permitted to be blended for use in all light vehicles, referred to as Blend Wall (BW), is currently at 10% (Renewable Fuels Association 2015). Note that light vehicles of model year later than 2000 as well as specially designed vehicles (Flex-fuel vehicles) are able to consume up to 15% and 85% bioethanol in their fuel, respectively (Yacobucci 2010; Ghahremanlou and Kubiak 2020c). The subsidy for blending bioethanol with gasoline comes through Tax Credits for US and foreign ethanol (TCL and TCI respectively), enacted by the 2004 Volumetric Ethanol Excise Tax Credit (McPhail et al. 2011). To support and lead US bioethanol production Tariffs for both foreign and US bioethanol blended with gasoline (TI and TL respectively) are considered (Ghahremanlou and Kubiak 2020c; McPhail et al. 2011). One may interpret the impact of Tax Credits and Tariffs on the SCOSC, as government subsidies and deterrents for surviving the SCOSC during the economic crises.

Although there has been a great deal of emphasis placed on SCOSCs, to the best of our knowledge only Andersen et al. (2013); Kazemzadeh and Hu (2013; 2015); Ghahremanlou and Kubiak (2020c;d;a;b;e) have studied them. Two models are developed by Andersen et al. (2013) to study, respectively, the investment requirement in each US region to create the SCOSC and fuel distribution in one state. They did not consider government policies, which are backbone of the SCOSC. Kazemzadeh and Hu (2013) employed risk neutral and risk averse approaches in their two models, in which they incorporated RFS2 and TCL. Later, they extended this work in Kazemzadeh and Hu (2015) to measure the impact of RFS2 and TCL on the SCOSC, which does not consider the existing infrastructures, and has only nine policy scenarios. Ghahremanlou and Kubiak (2020c) developed a risk neutral model, which included only 2^{nd} generation bioethanol, and used this to do a case study in Ghahremanlou and Kubiak (2020d). Ghahremanlou and Kubiak (2020a) extended their risk neutral model by including all existing infrastructures, and 1^{st} and 2^{nd} generation bioethanol, then conducted a case study in Ghahremanlou and Kubiak (2020b). The significance of creating new SCOSCs which can withstand economic crises is illustrated in Ghahremanlou and Kubiak (2020e); they employed a Conditional Value-at-Risk (CVaR) approach to hedge the SCOSC against financial risks. Their model focused on one of the 23 states (out of 50 states) which does not have any bio-refineries in place Renewable Fuels Association (2010), although the majority of states have infrastructure already in place which government and investors are trying to rescue in the current economic crisis. Therefore, there is no other study which provide insights for the government and investors how to lead and manage the SCOSC during economic crises, like the current one created by COVID-19 and the 2020 Saudi Arabia-Russia Oil Price War, and include all the policies: RFS2, TCL, TCI, TL, TI, and BW. In this paper we fill this gap by applying a CVaR approach, as a risk averse method, and run a computational experiments with 10,710 different policy scenarios, to provide insights on how to protect the SCOSC during crises. The CVaR was initially developed for minimization objective functions (Rockafellar and Uryasev 2000; 2002a), however, later on was proved for maximization objective functions (Ogryczak and Ruszczynski 2002), which is the case in this paper.

To put it concisely, our contributions in this paper are: (1) proposing a risk averse two-stage stochastic programming model by applying CVaR of expected profit maximization objective function; (2) determining the expected profit that SCOSC investors obtain during economic crisis for each policy scenario; (3) calculating the minimum subsidy that government needs to consider to make sure the SCOSC will survive during economic crisis; (4) pinpointing the policy scenarios resulting in energy security; (5) identifying the appropriate policy scenarios which may lead bio-refineries toward combating the COVID-19 pandemic; (6) illustrating social aspect of the SCOSC for each policy scenario; (7) recommending investors robust strategic investment decisions; (8) specifying the policy scenarios that result in survival of the SCOSC, most environmentally friendly fuel, and energy independency; and (9) providing strategic investment decisions resilient to varying economic conditions. The rest of this paper is structured as follows: Section 7.2 states the problem at hand, followed by its Mathematical programming model in Section 7.3. The information required to accomplish the case study and computational experiments are given in Sections 7.4 and 7.4.1. We analyze the results of the study from economic, environmental, and social perspectives in Section 7.5 and recommend some prudent decisions for government and industry. Further insights regarding the difference between decisions and expectations during economic crisis *vs* regular economic conditions are provided in Section 7.6. Finally, we summarize our findings and offer some avenues for further research in Section 7.7.

7.2 Problem Statement

The goal of the SCOSC is to meet the fuel demand for the light fuel vehicles within a state while complying with policies: RFS2, TCL, TCI, TI, TL, and BW. There are currently a set of 1^{st} and 2^{nd} generation bio-refineries in the state. Each county has its own harvesting sites for 1^{st} and 2^{nd} generation bioethanol, and distribution centers, located in the center of each county. Furthermore, the center of each county is a potential location for the new 1^{st} and 2^{nd} generation bio-refineries and blending sites. Bioethanol can be sold to corresponding exporters. It also may be imported from other states and abroad, if need be. Gasoline is bought from refineries and gasoline importers. Please see the schematic view of the SCOSC in Figure 7.1. Given the relationships in the figure, the flow between every two partners is permitted and is carried out by truck.

The primary objective function is CVaR of expected profit in the two stage stochastic programming model. After solving this objective function, we plug the results in the sec-

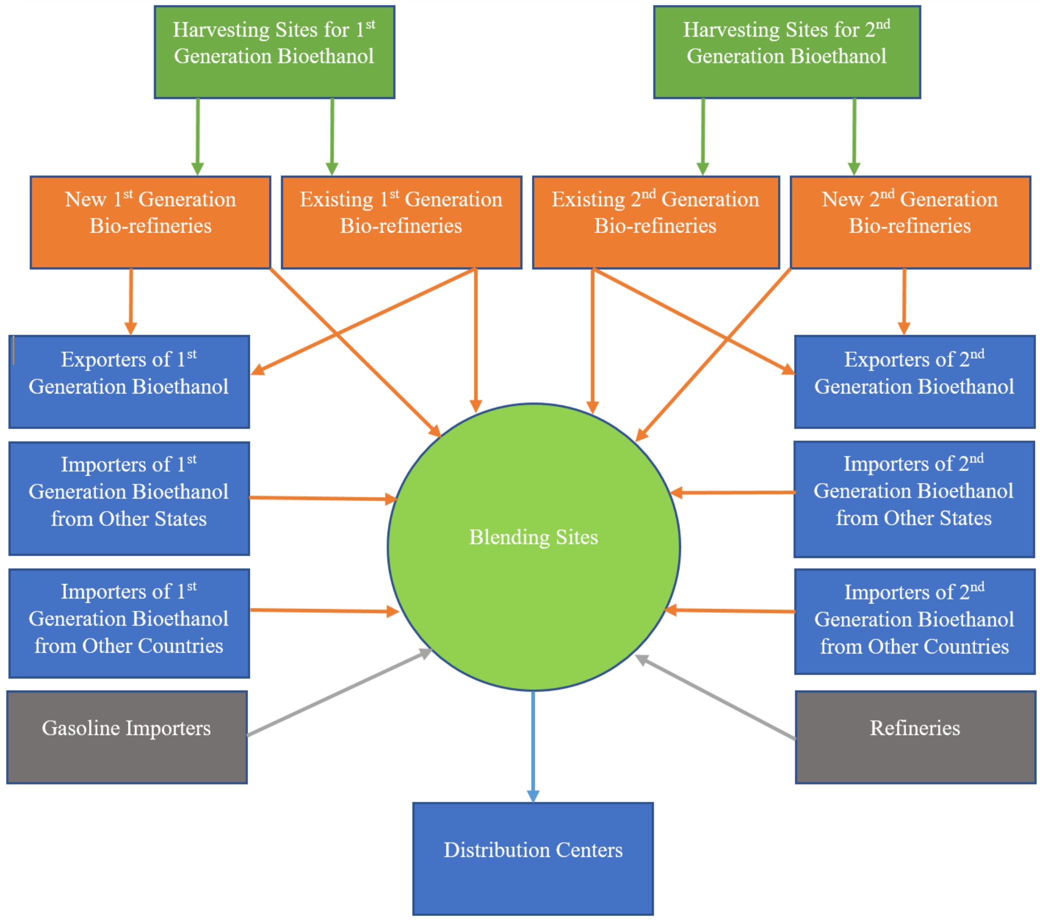


Figure 7.1: Sustainable Crude Oil Supply Chain Network

ondary objective function, expected number of jobs created during the 30 year lifetime of the SCOSC. For further details see Ghahremanlou and Kubiak (2020a), the risk neutral version of this study.

7.3 Formulation of Models

- CVaR of Expected Profit Maximization Objective Function – This objective function is as follows, by definition of CVaR, see Ogryczak and Ruszczynski (2002):

$$\max CVaR_{1-\xi}(L_1) = \zeta - \frac{1}{\xi} \cdot \sum_{s \in S} \omega_s \cdot \upsilon_s \tag{7.1}$$

where L_1 is the expected profit, $(1-\xi) \in [0,1]$ is $(1-\xi)$–quantile of the random profit, ζ and υ_s are respectively unrestricted and non-negative variables required due to linearization of the objective function, and ω_s is the probability of scenario $s \in S$.

- Expected Number of Jobs Created Maximization Objective Function – This objective function stays the same as its counterpart Ghahremanlou and Kubiak (2020a); however, we will see the values are changed in Section 7.6, since the optimal solution of $CVaR_{1-\xi}(L_1)$, instead of optimal solution of L_1, is plugged into the expected number of jobs created objective function, L_2.

- Constraints – To facilitate using the CVaR in optimization problem it is required to linearize the objective function, as it is above, which will add

$$\upsilon_s \geq \zeta - L_{1s}, \qquad \forall s \in S \tag{7.2}$$

and

$$\upsilon_s \geq 0, \qquad \forall s \in S \tag{7.3}$$

to the mathematical programming model (the proof is given by Ogryczak and Ruszczynski (2002)). To complete the model we require constraints (58)-(107), and for scenario $s \in S$ components (108)-(133), in Ghahremanlou and Kubiak (2020a).

7.4 Case Study

Corn and its by-product corn stover have made the US, the largest bioethanol producer globally (U.S. Department of Energy 2018). Therefore, we consider these two as the feedstock in this paper. Among the six states that make up over 70% of the US ethanol production, Iowa and Nebraska are the two largest respectively (U.S. Energy Information Administration 2018b). Li et al. (2015), Li and Hu (2014), Li et al. (2014), and Zhang and Hu (2013), are among the several papers studied Iowa; however, Nebraska, has exclusively been studied by Ghahremanlou and Kubiak (2020d) and Ghahremanlou and Kubiak (2020b). The latter paper most closely reflects that state's case, examining its existing infrastructures. Thus, we consider Nebraska for the purpose of the case study, and employ the data provided by Ghahremanlou and Kubiak (2020b). For the parameter of CVaR, by Kazemzadeh and Hu (2015), $\xi = 20\%$. This value guarantees the minimum expected profit that the investors on the SCOSC can obtain with probability $100\% - 20\% = 80\%$, which can match the risk preference of a wide range of investors in the current economic crisis resulting from COVID-19 and the 2020 Saudi Arabia-Russia Oil Price War.

7.4.1 Design of Computational Experiments

For the purpose of this paper, we consider the following policies, as mentioned in Section 7.2:

1. RFS2 mandate for cellulosic bioethanol ($\beta \cdot \overline{\overline{R}}$);
2. Tax Credit for Local bioethanol blended with gasoline ($TCL = \eta \cdot T$, $\forall \eta \geq 0$);
3. Tax Credit for Imported bioethanol from abroad blended with gasoline ($TCI = \theta \cdot \overline{T}$, $\forall \theta \geq 0$);

4. Tariff for Local bioethanol blended with gasoline ($TL = -\eta \cdot T, \forall \eta \leq 0$);

5. Tariff for Imported bioethanol from abroad blended with gasoline ($TI = -\theta \cdot \overline{T}, \forall \theta \leq 0$);

6. Blend Wall (α).

Recall Section 7.1, $T = 0.45$ and $\overline{T} = 0.54 \frac{\$}{\text{gal}}$. The η, θ, β, and α are coefficients that take the values below:

- $\eta = -3.18 + 0.4 \cdot k, \forall k = 0, 1, ..., 15;$
- $\theta = -2.65 + 0.4 \cdot k, \forall k = 0, 1, ..., 13;$
- $\beta = 0.3 \cdot k, \forall k = 0, 1, ..., 12;$
- $\alpha = 10\%, 15\%, 85\%;$

Additionally, the values 3.76, 3.18 and 2.65 are respectively inserted to the discretized sets of β,η and θ (Ghahremanlou and Kubiak 2020b). This generates $3 \cdot 14 \cdot 15 \cdot 17 = 10,710$ different policy scenarios. The optimization problem for each policy scenario consists of 1,224 continuous variables, 5,780 binary variables, and 1,156 constraints. The model is coded in Python 2.7 (Python Software Foundation 2001), and it is solved to optimality using Gurobi 7.0 (Gurobi Optimizer LLC. 2008). We ran the experiments on a Dell computer with an Intel Core i5-2400 3.10 GHz CPU and 8 GB RAM.

7.5 Analysis of Results, and Recommendations

The concept of sustainability, which stands on economic, environmental and social pillars, has gained prominence in the context of business management (Ahi and Searcy 2013).

This has attracted many researchers, some of the recent ones being Oelze (2017); Zimon and Domingues (2018); Patel and Desai (2019). The sustainability within oil industry, providing over 90% of the global transportation fuel demand, is a vital element which was initiated in response to environmental and energy security policies (Sahebi et al. 2014a). Therefore, we report our results from economic, environmental, and social perspectives below.

We employ the algorithm used by Ghahremanlou and Kubiak (2020a), and find optimal solution for $CVaR_{1-\xi}(L_1)$, for minimum transportation distance and maximum transportation distance, deriving respectively X_{min}, referred to as the best case, and X_{max}, referred to as the worst case. Then $L_2(X_{\min})$ and $L_2(X_{\max})$ are calculated by plugging $X_{\min}$ and $X_{\max}$ into L_2.

7.5.1 Economic Perspective

The economic slowdown has a direct relation with job insecurity, psychological and physical health, and the standard of living (De Witte et al. 2015; Steckel 2002). Research illustrates that oil crises result in the US economic crises (Steckel 2002). To avoid this the US has employed its military power to capture oil resources in other countries. These oil wars resulted in the deaths of over half a million Americans (Heinberg 2005; Hedges 2003). Therefore, economic growth, in particular that based on the SCOSC, is important.

Figures 7.2 and 7.3 show the maximum CVaR of expected profit, $CVaR_{1-\xi}(L_1)$, that investors can gain in the best case, $CVaR_{1-\xi}(L_1(X_{\min}))$, and $CVaR_{1-\xi}(L_1(X_{\max}))$, in the worse case, respectively. We observe that $CVaR_{1-\xi}(L_1(X_{\min}))$ and $CVaR_{1-\xi}(L_1(X_{\max}))$ are sensitive to α, β, θ, and η.

A side-by-side examination of plots (a) and (b), (c) and (d), (e) and (f) demonstrates that for any α, θ, and η the $CVaR_{1-\xi}(L_1)$ decreases when β, represented by the colorbar, increases (as the back views are colored yellow, which represents highest values of β, and the front views are colored blue, which represents the lowest values of β).

The three plots in red, blue and green in Figures 7.2 (g) and 7.3 (g) are respectively the three projections of $CVaR_{1-\xi}(L_1(X_{\min}))$ and $CVaR_{1-\xi}(L_1(X_{\max}))$, for $\alpha = 10\%$, 15% and 85%, fixed β, and variable η and θ. These plots show for any β, η, and θ, with increasing α, $CVaR_{1-\xi}(L_1)$ will increase, for $\eta \geq 0.02$, equivalent to at least $TCL \geq 0.02 \cdot 0.45 = 0.009$ $\frac{\$}{\text{gal}}$ tax credit for US bioethanol blended with gasoline, see Section 7.5.2; in this condition US bioethanol is blended with gasoline.

The comparison of the two figures for different α (e.g. plots (a) in Figures 7.2 and 7.3 for $\alpha = 10\%$) demonstrates that $CVaR_{1-\xi}(L_1(X_{\min}))$ and $CVaR_{1-\xi}(L_1(X_{\max}))$ follow the same pattern, however, for any α, β, θ, and η, $CVaR_{1-\xi}(L_1(X_{\min})) \geq CVaR_{1-\xi}(L_1(X_{\max}))$. We define the following numerical indices to respectively calculate maximum, minimum and average difference between $CVaR_{1-\xi}(L_1(X_{\min}))$ and $CVaR_{1-\xi}(L_1(X_{\max}))$, for any policy scenario (α, β, θ, and η):

1. $CVaRMaxD^{\alpha} = \max_i \{CVaR_{1-\xi}(L_1(X_{\min}(\alpha,i))) - CVaR_{1-\xi}(L_1(X_{\max}(\alpha,i)))\}$;
2. $CVaRMinD^{\alpha} = \min_i \{CVaR_{1-\xi}(L_1(X_{\min}(\alpha,i))) - CVaR_{1-\xi}(L_1(X_{\max}(\alpha,i)))\}$;
3. $CVaRAD^{\alpha} = \dfrac{\sum_{i=1}^{i=3570} \left[CVaR_{1-\xi}(L_1(X_{\min}(\alpha,i))) - CVaR_{1-\xi}(L_1(X_{\max}(\alpha,i)))\right]}{3570}$.

For different values of α, the $X_{\min}(\alpha,i)$ and $X_{\max}(\alpha,i)$ are the optimal solutions for the best and the worst case respectively, and the i-th combination of β, θ, and η for $i = 1,2,...,3570$ (the 3570 is number of combinations of β, θ, and η for any α, $14 \cdot 15 \cdot 17 = 3570$, see Section 7.4.1). Accordingly, in our experiments the values of the indices in millions of dollars are as follows:

- $CVaRMaxD^{10\%} = 491.393$ and $CVaRMaxD^{15\%} = 492.213$;

- $CVaRMaxD^{85\%} = 507.245$ and $CVaRMinD^{10\%} = 486.688$;
- $CVaRMinD^{15\%} = 487.622$, and $CVaRMinD^{85\%} = 491.38$;
- $CVaRAD^{10\%} = 488.716$, $CVaRAD^{15\%} = 488.817$, and $CVaRAD^{85\%} = 503.310$.

Whenever US bioethanol is blended with gasoline, $\eta \geq 0.02$, equivalent to $TCL \geq 0.02 \cdot 0.45 = 0.009\ \frac{\$}{\text{gal}}$ tax credit for US bioethanol blended with gasoline, see Section 7.5.2, with increasing η, for any α, β, and θ, $CVaR_{1-\xi}(L_1)$ will increase. Likewise, where $\theta \geq 0.15$, equivalent to $TCI \geq 0.15 \cdot 0.54 = 0.81\ \frac{\$}{\text{gal}}$ tax credit for foreign bioethanol blended with gasoline, foreign bioethanol is blended with gasoline, with increasing θ, other policies fixed, $CVaR_{1-\xi}(L_1)$ will increase.

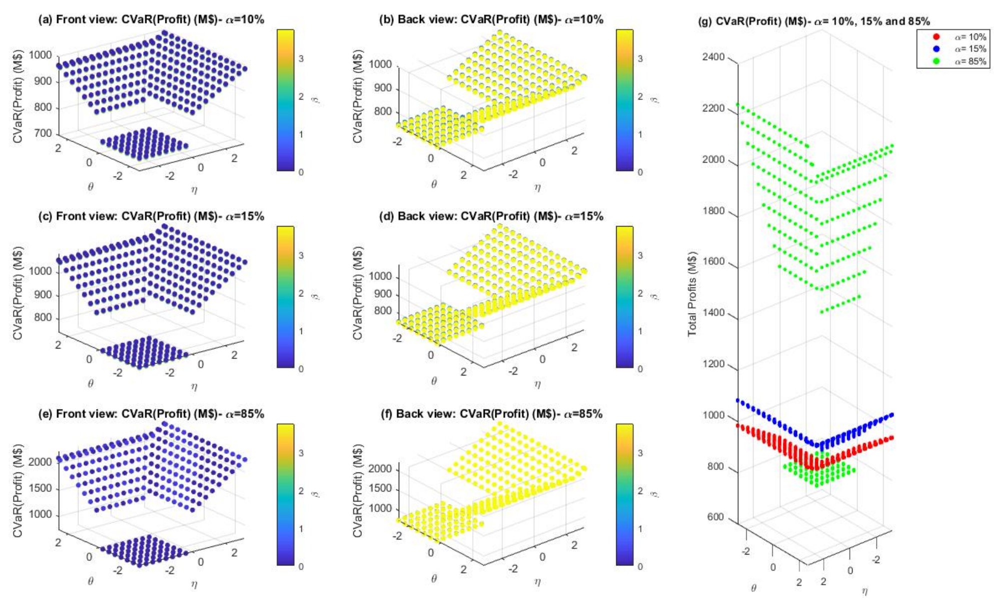


Figure 7.2: $CVaR_{1-\xi}(L_1(X_{\min}))$, $\alpha = 10\%, 15\%$ and 85%

Vimmerstedt et al. (2012) argue that the BSC, which is the source of sustainability in the SCOSC, requires continuing US government subsidy for its survival. There are some recent subsidy packages for bio-refineries due to COVID-19, see Paycheck Protection Program

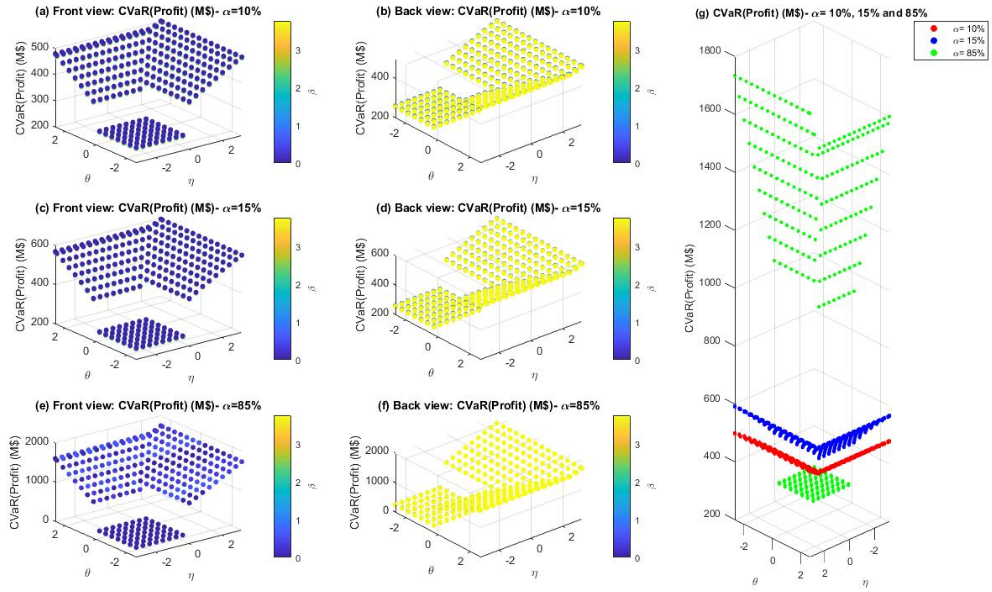


Figure 7.3: $CVaR_{1-\xi}(L_1(X_{\max}))$, $\alpha = 10\%, 15\%$ and 85%

under Coronavirus Aid, Relief, and Economic Security (CARES) Act American Coalition for Ethanol (2020). Therefore, we calculate minimum government subsidy that can help bio-refineries to survive the current economic crisis, by defining $Minimum\ \eta(\alpha, \beta, \theta)$, being the minimum η, if any, such that $CVaR_{1-\xi}(L_1(X_{\min})) > 0$ ($CVaR_{1-\xi}(L_1(X_{\max})) > 0$) for given α, θ, and β. The $Minimum\ \eta(\alpha, \beta, \theta) = -3.18$ for any α, θ, and β. This implies that government does not subsidize the SCOSC. However, we would like to emphasize that this is the case for the collaborative supply chain which we stated in Section 7.2.

7.5.2 Environmental Perspective

A primary objective of blending bioethanol with gasoline is to combat global warming which is already having a profound effect on many species and their ecosystems (Ahima 2020; Hunt et al. 2020; Vicente-Serrano et al. 2020). Therefore, we determine the average amount of bioethanol blended with gasoline over all 36 scenarios, for each policy scenario, by defining B^{α} (Ghahremanlou and Kubiak 2020b):

$$B^{\alpha} = \left(\frac{\sum_{s=1}^{36} \frac{e_s^{E1} + e_s^{E2} + e_s^{N1} + e_s^{N2} + h_s^{C} + h_s^{CS} + k_s^{C} + k_s^{CS}}{D_s}}{36} \right) \cdot 100. \quad (7.4)$$

Figure 7.4 shows B^{α} (see equation (7.4), for the best and worst case, for any policy scenario (α, β, θ and η). We observe, B^{α} is sensitive to all policies, except whenever $B^{\alpha} \neq 0$. With increasing any of the policies, B^{α} may increase. Each plot in the figure has two main parts: (1) $B^{\alpha} = 0$, which occurs whenever $\theta \leq -0.25$, equivalent to minimum $TI \geq 0.25 \cdot 0.54 = 0.135 \frac{\$}{\text{gal}}$ tariff for foreign bioethanol blended with gasoline, and $\eta \leq -0.38$, equivalent to minimum $TL \geq 0.38 \cdot 0.45 = 0.171 \frac{\$}{\text{gal}}$ tariff for US bioethanol blended with gasoline; (2) $\frac{2}{3} \cdot \alpha < B^{\alpha} \leq \alpha$, for $\theta \geq 0.15$, equivalent to minimum $TCI \geq 0.15 \cdot 0.54 = 0.81 \frac{\$}{\text{gal}}$ tax credit for foreign bioethanol blended with gasoline, or $\eta \geq 0.02$, equivalent to at least $TCL \geq 0.02 \cdot 0.45 = 0.009 \frac{\$}{\text{gal}}$ tax credit for US bioethanol blended with gasoline.

We observe that whenever bioethanol is not blended with gasoline it is produced and sold to the exporters, see Sections 7.5.4.1 and 7.5.4.2. In the current situation, the US government is effectively trying to defend itself from a double barrel blast: on one hand it is trying to combat COVID-19, in part by ensuring there is sufficient production of sanitizer for its citizens, while on the other hand, it finds itself having to rescue bio-refineries from bankruptcy due to the 2020 Saudi Arabia-Russia Oil Price War, as well as the crippling global impact of COVID-19 on this industry. Thus, it might be worthwhile, on the part of government and investors, to consider steering production away from bioethanol and toward production of sanitizers. Government can accomplish this by enacting at least 0.135 and 0.171 $\frac{\$}{\text{gal}}$ tariff for foreign and US bioethanol blended with gasoline respectively. Furthermore, researchers believe hydrogen is the energy of the future, and can bring about fossil fuel independence and emissions free transportation fuel (Chamousis 2009); for more details see Nuttall and Bakenne (2019). Therefore, to stop using bioethanol, and employ hydrogen as a transportation fuel, the same tariffs are required.

Our experiments show that whenever $\frac{2}{3} \cdot \alpha < B^{\alpha} \leq \alpha$, both types of bioethanol, 1^{st} and 2^{nd} generation, from existing bio-refineries are blended with gasoline. Bioethanol from new 2^{nd} generation bio-refineries is not blended with gasoline at all. This is a good indication of the significance of existing bio-refineries in the production of environmentally friendly fuel, and consequently a sustainable economy, which is also recently emphasized by Lane (2020).

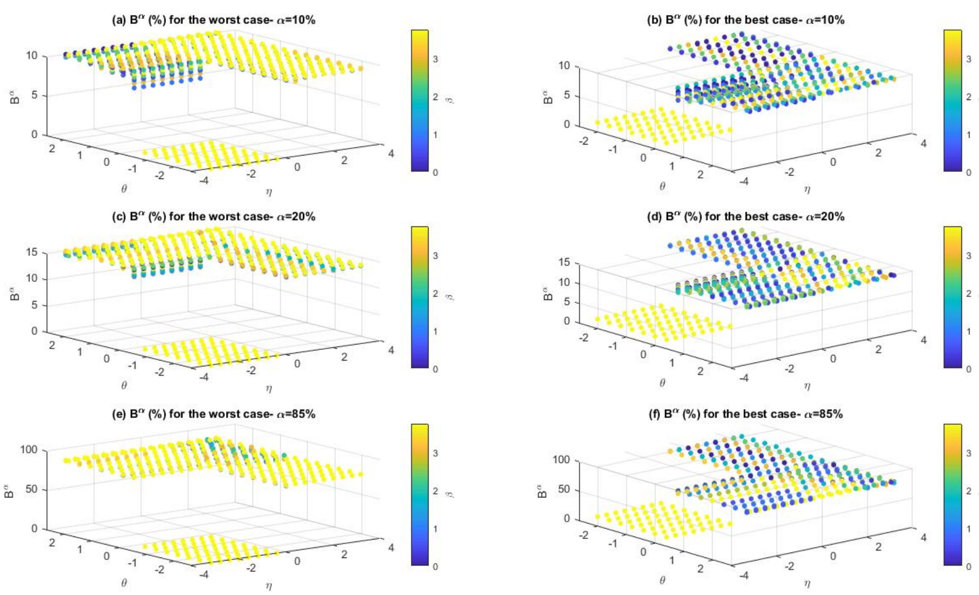


Figure 7.4: B^{α} for the best and worst case, $\alpha = 10\%, 15\%$ and 85%

7.5.3 Social Perspective

The important role of bioethanol production in the development of the US rural areas, by creating jobs, was undoubted since its beginning (Petrulis 1993). Additionally, Usmani

(2020) recently conducted research illustrating the significance of the bio-refineries in improving the socioeconomic situation of the US, in particular that of farmers. The social perspective of the SCOSC has attracted other researchers, see You and Wang (2011); You et al. (2012), to measure the expected number of jobs created throughout the supply chain, although none considered the policies. The US farmers have recently been triple impacted: by RFS2 waivers, COVID-19 and the 2020 Saudi Arabia-Russia Oil Price War (Pamuk and Singh 2020; Shearer 2020). The farmers have recently asked the government to provide immediate financial support to them due to the severity of the economic trauma they have suffered (The Poultry Site 2020). Figure 7.5 provides the government with some insights about the social perspective of their decisions in terms of policy scenarios, in Nebraska during a 30 year time frame set for the SCOSC, in the best and worst case. The expected number of jobs, L_2, is sensitive to α, β, θ, or η, but not following a specific pattern. Therefore, to find out the maximum expected number of jobs for the best and worst case, respectively $MaxJB^{\alpha}$ and $MaxJW^{\alpha}$, and minimum expected number of jobs for the best and worst case, respectively $MinJB^{\alpha}$ and $MinJW^{\alpha}$, for any α and $i = 1, 2, ..., 3570$ (i is a combination of β, θ, and η), we define the following:

1. $MaxJB^{\alpha} = \max_i \{L_2(X_{\min}(\alpha, i))\}$ and $MaxJW^{\alpha} = \max_i \{L_2(X_{\max}(\alpha, i))\}$;
2. $MinJB^{\alpha} = \max_i \{L_2(X_{\min}(\alpha, i))\}$ and $MinJW^{\alpha} = \max_i \{L_2(X_{\max}(\alpha, i))\}$.

We derive

- $MaxJB^{10\%} = 513,215$, for $\beta = 0$, $\theta = 1.75$, and $\eta = 0.02$;
- $MaxJB^{15\%} = 513,586$, for $\beta = 1.5$, $\theta = 1.35$, and $\eta = 3.18$;
- $MaxJB^{85\%} = 624,076$, for $\beta = 3.76$, $\theta = 0.55$, and $\eta = 0.42$;
- $MaxJW^{10\%} = 1,345,653$, for $\beta = 2.4$, $\theta = 0.95$, and $\eta = -3.18$;

- $MaxJW^{15\%} = 1,309,426$, for $\beta = 1.8$, $\theta = 0.15$, and $\eta = -3.18$;
- $MaxJW^{85\%} = 1,288,535$, for $\beta = 0.9$, $\theta = -2.65$, and $\eta = -3.18$;
- $MinJB^{10\%} = 511,192$, for $\beta = 1.8$, $\theta = 2.65$, and $\eta = 2.42$;
- $MinJB^{15\%} = 511,220$, for $\beta = 0.3$, $\theta = 0.95$, and $\eta = -3.18$;
- $MinJB^{85\%} = 511,818$, for $\beta = 3$, $\theta = -2.65$, and $\eta = -3.18$;
- $MinJW^{10\%} = 1,075,300$, for $\beta = 0.3$, $\theta = 2.55$, and $\eta = 0.42$;
- $MinJW^{15\%} = 889,623$, for $\beta = 0$, $\theta = 2.55$, and $\eta = 0.02$;
- $MinJW^{85\%} = 868,809$, for $\beta = 3.76$, $\theta = 2.65$, and $\eta = 1.22$.

We observe that for any α, $MaxJW^{\alpha} > MaxJB^{\alpha}$ and $MinJW^{\alpha} > MinJB^{\alpha}$; also, a stronger condition holds: $L_2(X_{\max}(\alpha,i)) > L_2(X_{\min}(\alpha,i))$, for any α and i. This implies that when the distance between counties is greater, the number of expected jobs created will be greater; the less distance involved, the fewer jobs created. This can be attributed to transportation, and capacity and number of facilities.

7.5.4 Further Strategic and Managerial Insights

Strategic decisions require the greatest deal of investment and last the longest within any supply chain. These decisions have a lifespan of 5 to 30 years in the SCOSC (Sahebi et al. 2014b; Kazemzadeh and Hu 2015). Therefore, it is important to make robust strategic decisions against policy changes, since it might result in bankruptcy of the SCOSC, see bankruptcy of Philadelphia Energy Solutions, blaming RFS2 (Renshaw 2018). This will be our focus in the coming two subsections by discussing new facilities to be set up: (1) the numbers of new 1^{st} generation bio-refineries: r_1^{N1}, r_2^{N1}, r_3^{N1}, r_4^{N1}, and r_5^{N1} with capacities

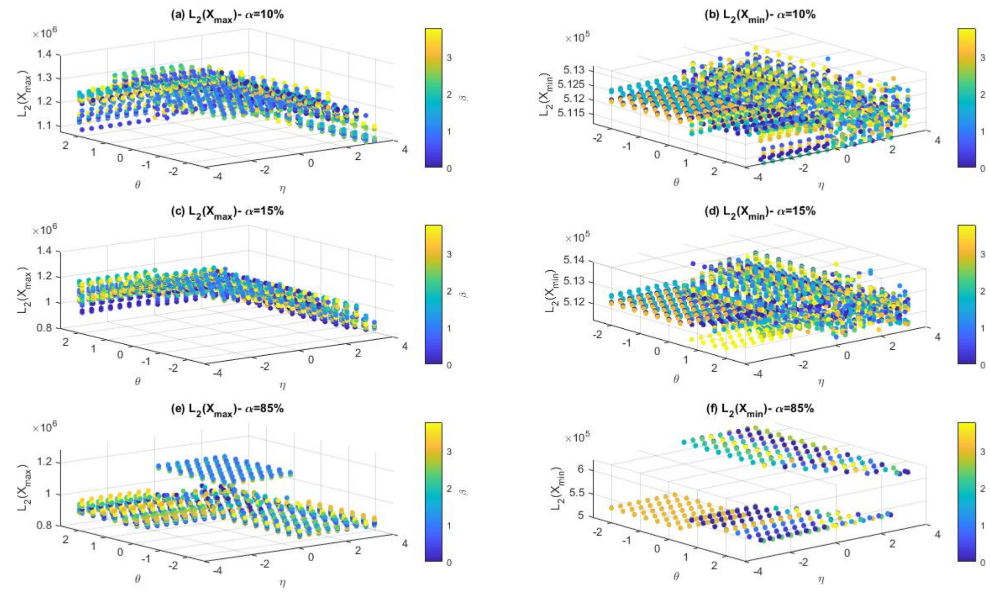


Figure 7.5: Number of jobs for the worst case and the best case, $\alpha = 10\%$, 15% and 85%

$U_1^{N1} = 7,960$, $U_2^{N1} = 39,800$, $U_3^{N1} = 79,600$, $U_4^{N1} = 159,200$, and $U_5^{N1} = 238,800$ $\frac{MT}{\text{y}}$, respectively; (2) the numbers of new 2^{nd} generation bio-refineries: r_1^{N2}, r_2^{N2}, and r_3^{N2} with capacities $U_1^{N2} = 772,151$, $U_2^{N2} = 1,544,303.78$, and $U_3^{N2} = 2,316,455.67$ $\frac{MT}{\text{y}}$, respectively; and (3) the numbers of new blending sites: b_1, b_2, b_3, b_4, b_5, and b_6 with capacities $H_1 = 36.59$, $H_2 = 109.77$, $H_3 = 182.95$, $H_4 = 256.13$, $H_5 = 329.31$, and $H_6 = 402.49$ $\frac{M\text{gal}}{\text{y}}$, respectively. Also, we discuss the robust numbers, locations, and capacities for these facilities as a part of our recommendations for investors and government.

So far, we have learned that a minimum $TCI \geq 0.81$ $\frac{\$}{\text{gal}}$ tax credit for foreign bioethanol blended with gasoline, or at least $TCL \geq 0.009$ $\frac{\$}{\text{gal}}$ tax credit for US bioethanol blended with gasoline will result in positive expected profit and the most environmentally friendly fuel. In this situation Nebraska is dependent on foreign bioethanol. To solve this issue, making Nebraska independent on foreign bioethanol, at the very least a $TI \geq 0.135$ $\frac{\$}{\text{gal}}$ tariff for foreign bioethanol blended with gasoline must be considered.

7.5.4.1 For $\alpha = 10\%$ and 15%

Table 7.1 reports on how the new facilities should be set up, for $\alpha = 10\%$ and 15%, in the best and worst case. We observe the numbers and capacities of the new facilities are sensitive to all elements of each policy scenario, α, β, θ, and η. Some of the cells in the table refer to a particular figure, the numbers of these facilities are β dependent, thus they have been demonstrated in separate figures. For example, for r_3^{N1} in the worst case and $\alpha = 10\%$ is written Fig.7.6, which means see Figure 7.6 for information. The Figures 7.6, 7.7, 7.8, and 7.9 are plotted for this purpose. This implies the significant role of RFS2 in strategic decisions with the risk averse preference, which is, overall, the case during economic crises. Below we recommend some strategic decisions which are robust against policy changes and stay the same in the best and worst case.

- *Bio-refineries.* For $\theta \leq -0.25$, equivalent to minimum $TI \geq 0.25 \cdot 0.54 = 0.135$ $\frac{\$}{\text{gal}}$ tariff for foreign bioethanol blended with gasoline, and $\eta \leq -0.38$, equivalent to minimum $TL \geq 0.38 \cdot 0.45 = 0.171$ $\frac{\$}{\text{gal}}$, setting a new 1^{st} generation bio-refinery with capacity $238,800$ $\frac{MT}{\text{y}}$ at: Adams, Butler, Chase, Custer, Fillmore, Gage, Hall, Howard, Jefferson, Kearney, Keith, and Seward counties, is robust.

- *Blending sites.* Establishing a blending site with capacity 109.77 $\frac{M\text{gal}}{\text{y}}$ at Sarpy county is robust.

7.5.4.2 For $\alpha = 85\%$

Tables 7.2 and 7.3 display the number of bio-refineries and blending sites, in the best and worst case, for $\alpha = 85\%$, β, θ, and η. Since β has no influence it is omitted from the tables. The set A, with its complement A^c, in the table is defined as follows:

	The worst case		The best case	
	$\alpha = 10\%$	$\alpha = 15\%$	$\alpha = 10\%$	$\alpha = 15\%$
r_1^{N1}	0	0	0	0
r_2^{N1}	0	0	0	$\begin{cases} 0 & if \quad otherwise \\ 1 & if \quad \eta = 0.02, \theta \in [-2.65, 0.15] \\ & \quad\;\; \eta = 0.42, \theta \in [-2.65, 0.55] \end{cases}$
r_3^{N1}	$Fig.$7.6	$Fig.$7.8	0	$Fig.$7.9
r_4^{N1}	$Fig.$7.6	$Fig.$7.8	$Fig.$7.7	$Fig.$7.9
r_5^{N1}	$Fig.$7.6	$Fig.$7.8	$Fig.$7.7	$Fig.$7.9
r_1^{N2}	0	0	0	0
r_2^{N2}	0	0	1	1
r_3^{N2}	0	0	2	2
b_1	$Fig.$7.6	$Fig.$7.8	0	0
b_2	1	1	1	1
b_3	1	1	0	0
b_4	0	$Fig.$7.8	0	0
b_5	1	$Fig.$7.8	0	0
b_6	0	0	2	2

Table 7.1: The β independent strategic decisions for the worst case and the best case, $\alpha = 10\%$ and 15%

$$A = A_1 \cup A_2 \cup A_3 \cup A_4 \cup A_5 \cup A_6 \cup A_7 \tag{7.5}$$

and

- $A_1 = \{(\eta, \theta) | \eta \in [-3.18, -0.38], \theta \in [-2.65, 2.65]\}$
- $A_2 = \{(\eta, \theta) | \eta = 0.02, \theta \in [0.55, 2.65]\}$
- $A_3 = \{(\eta, \theta) | \eta = 0.42, \theta \in [0.95, 2.65]\}$
- $A_4 = \{(\eta, \theta) | \eta = 0.82, \theta \in [1.35, 2.65]\}$
- $A_5 = \{(\eta, \theta) | \eta = 1.22, \theta \in [1.75, 2.65]\}$
- $A_6 = \{(\eta, \theta) | \eta = 1.62, \theta \in [2.15, 2.65]\}$

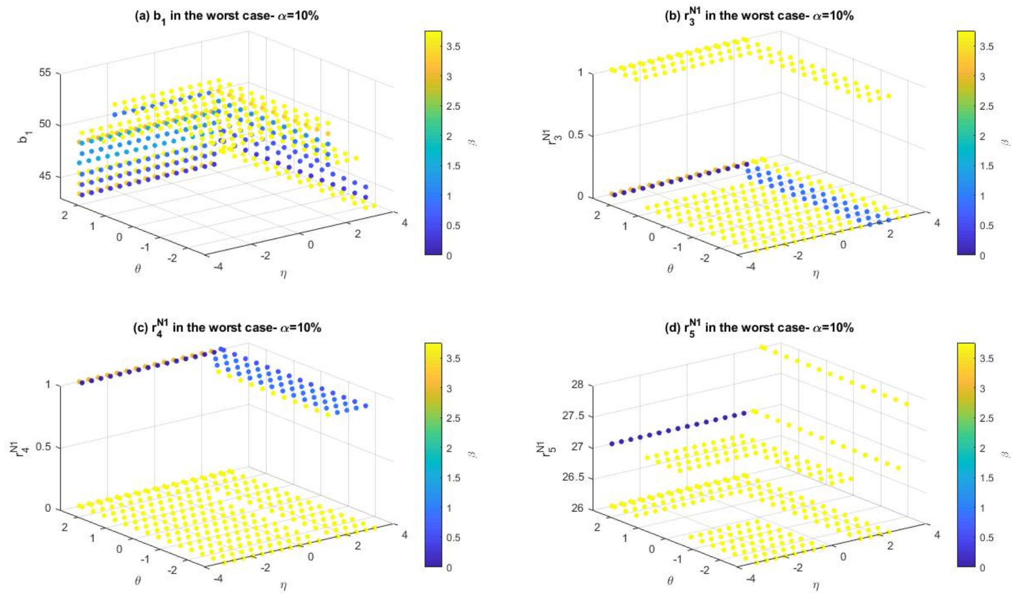


Figure 7.6: The β dependent strategic decisions for the worst case, $\alpha = 10\%$

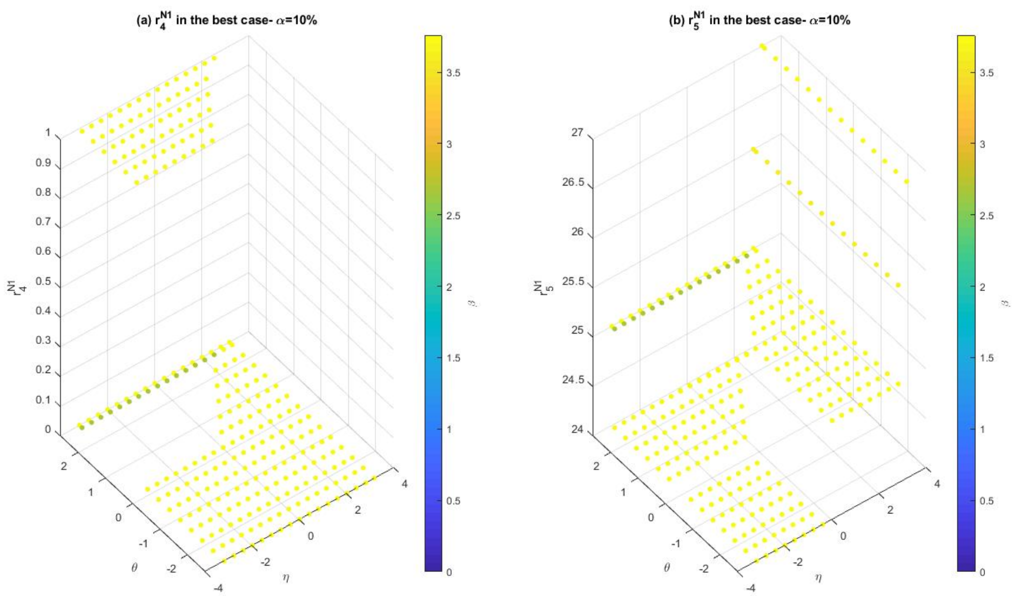


Figure 7.7: The β dependent strategic decisions for the best case, $\alpha = 10\%$

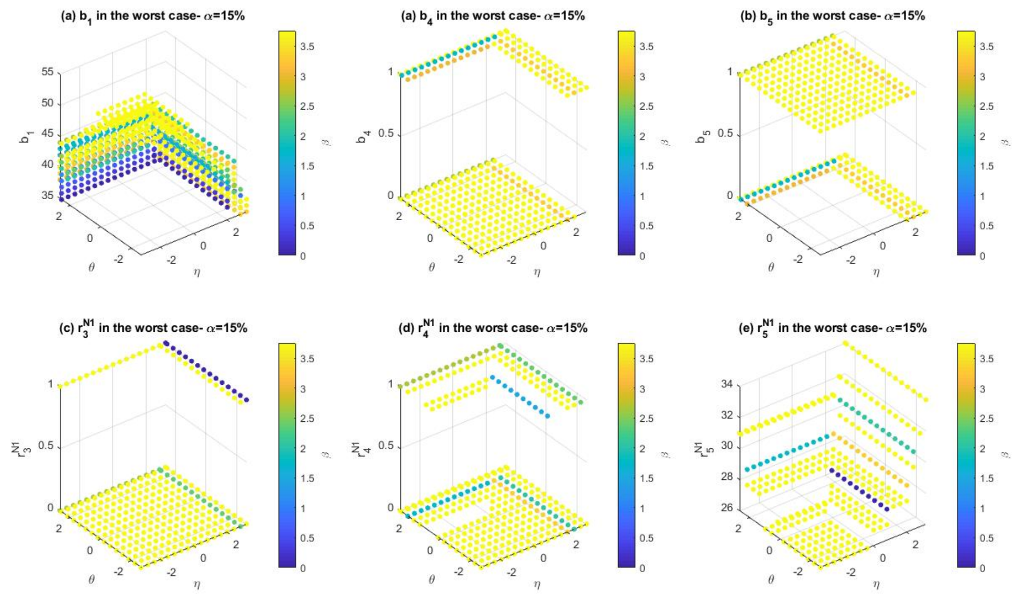


Figure 7.8: The β dependent strategic decisions for the worst case, $\alpha = 15\%$

- $A_7 = \{(\eta,\theta)|\eta \in [2.02, 2.42], \theta \in [2.55, 2.65]\}$.

We observe that the number of blending sites and bio-refineries is sensitive to η and θ. Below we provide the investors with some strategic decision recommendations which are robust against against policy changes and stay the same in the best and worst case.

- *Bio-refineries.* Establishing a 1^{st} generation bio-refinery with capacity $U_5^{N1} = 238,800$ $\frac{MT}{\mathrm{y}}$ at: Burt, Butler, Chase, Custer, Fillmore, Gage, Hall, Howard, Jefferson, Kearney, Keith, and Seward, is robust.

- *Blending sites.* For $(\eta,\theta) \in A^c$, establishing a blending site with capacity 36.59 $\frac{M\mathrm{gal}}{\mathrm{y}}$ at: Adam, Burt, Dawson, Hall, Lincoln, Platte, and Saunders county is robust. In contrast, for $(\eta,\theta) \in A$, setting up a blending site with capacity 109.77 $\frac{M\mathrm{gal}}{\mathrm{y}}$ at Sarpy county is robust.

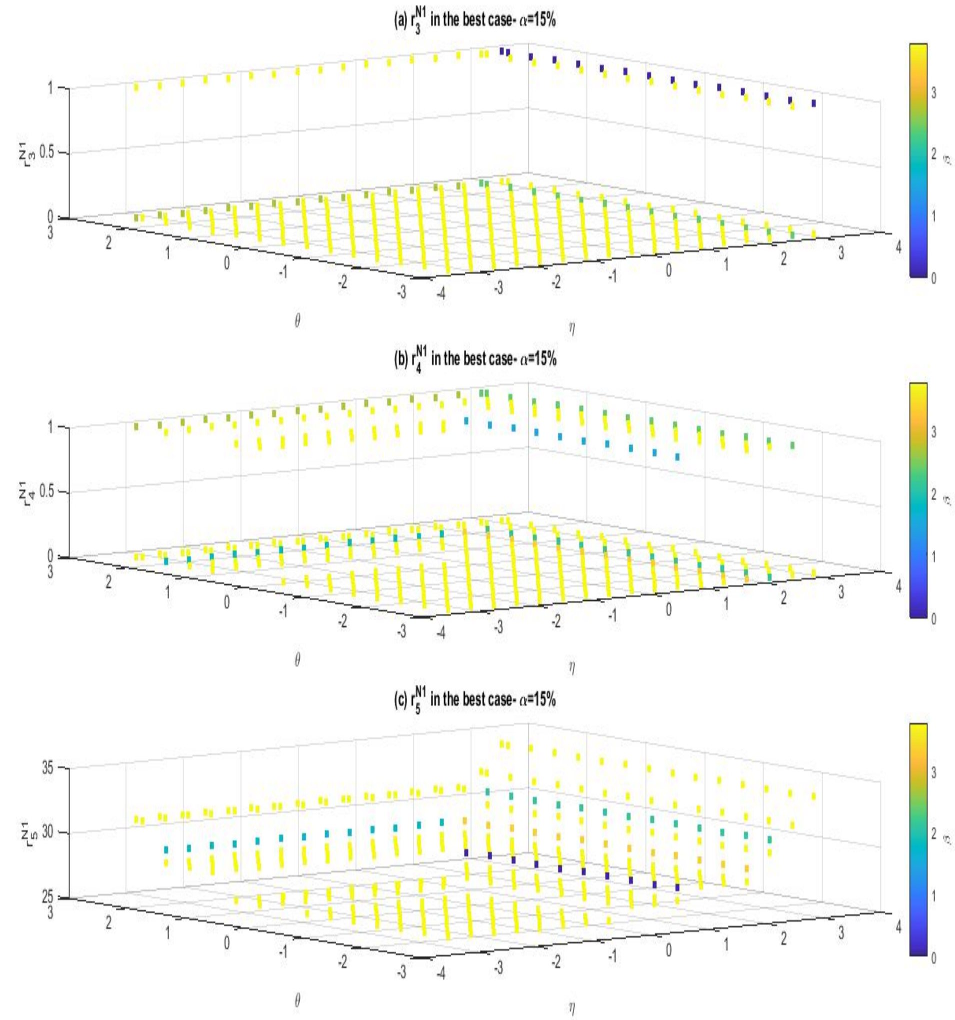


Figure 7.9: The β dependent strategic decisions for the best case, $\alpha = 15\%$

7.6 Comparison

As a part of this paper we report on the importance of employing risk averse approach, CVaR of expected profit, dealing with the economic crises like the one created by COVID-19 and the 2020 Saudi Arabia-Russia Oil Price War, as compared to the risk neutral approach, expected profit, in Ghahremanlou and Kubiak (2020b). Additionally, we provide

	$\alpha = 85\%$	
	The worst case	The best case
r_1^{N1}	0	0
r_2^{N1}	0	0
r_3^{N1}	0	0
r_4^{N1}	0	0
r_5^{N1}	$\begin{cases} 26 & if \quad \eta \in [-3.18,-0.38], \\ & \quad \theta \in [-2.65,-0.25] \\ 56 & if \quad \eta \notin [-3.18,-0.38], \\ & \quad \theta \notin [-2.65,-0.25] \end{cases}$	$\begin{cases} 24 & if \quad \eta \in [-3.18,-0.38], \theta \in [-2.65,-0.25] \\ 48 & if \quad \eta \in [-3.18,-0.38], \theta = 0.15 \\ 56 & if \quad \eta \in [-3.18,3.18], \theta \in [0.55,2.65] \\ & \quad \eta \in [0.02,3.18], \theta \in [-2.65,0.15] \end{cases}$
r_1^{N2}	0	0
r_2^{N2}	0	$\begin{cases} 0 & if \quad \eta \notin [-3.18,-0.38], \theta \notin [-2.65,-0.25] \\ 1 & if \quad \eta \in [-3.18,-0.38], \theta \in [-2.65,-0.25] \end{cases}$
r_3^{N2}	0	$\begin{cases} 2 & if \quad \eta \in [-3.18,-0.38], \theta \in [-2.65,-0.25] \\ 3 & if \quad \eta \notin [-3.18,-0.38], \theta \notin [-2.65,-0.25] \end{cases}$

Table 7.2: The number of bio-refineries for the worst case and the best case, $\alpha = 85\%$

	$\alpha = 85\%$	
	The worst case	The best case
b_1	$\begin{cases} 35 & if \quad \eta \notin [-3.18,-0.38], \\ & \quad \theta \notin [-2.65,-0.25] \\ 53 & if \quad \eta \in [-3.18,-0.38], \\ & \quad \theta \in [-2.65,-0.25] \end{cases}$	$\begin{cases} 0 & if \quad A \\ 7 & if \quad A^c \end{cases}$
b_2	$\begin{cases} 1 & if \quad \eta \in [-3.18,-0.38], \\ & \quad \theta \in [-2.65,-0.25] \\ 2 & if \quad \eta \notin [-3.18,-0.38], \\ & \quad \theta \notin [-2.65,-0.25] \end{cases}$	$\begin{cases} 1 & if \quad A \\ 0 & if \quad A^c \end{cases}$
b_3	1	0
b_4	0	$\begin{cases} 0 & if \quad A \\ 1 & if \quad A^c \end{cases}$
b_5	$\begin{cases} 0 & if \quad \eta \notin [-3.18,-0.38], \\ & \quad \theta \notin [-2.65,-0.25] \\ 1 & if \quad \eta \in [-3.18,-0.38], \\ & \quad \theta \in [-2.65,-0.25] \end{cases}$	0
b_6	0	$\begin{cases} 2 & if \quad A \\ 1 & if \quad A^c \end{cases}$

Table 7.3: The number of blending sites for the worst case and the best case, $\alpha = 85\%$

strategic investment decisions that can withstand the economic crises due to being resilient to risk preferences.

1. *Economic Perspective* – To measure the expected profit that the investors on the SCOSC may loose due to economic crises, we calculate:

   (a) maximum difference between expected profit and the CVaR of expected profit in the best case;

   (b) maximum difference between expected profit and the CVaR of expected profit in the worst case;

   (c) minimum difference between expected profit and the CVaR of expected profit in the best case;

   (d) minimum difference between expected profit and the CVaR of expected profit in the worst case;

   (e) average difference between expected profit and the CVaR of expected profit in the best case;

   (f) average difference between expected profit and the CVaR of expected profit in the worst case;

   for any given α and i being a policy combination (β, θ, and η), by respectively defining:

   (a) $MaxDMin^{\alpha} = \max_i \{L_1(X_{\min}(\alpha,i)) - CVaR_{1-\xi}(L_1(X_{\min}(\alpha,i)))\}$;

   (b) $MaxDMax^{\alpha} = \max_i \{L_1(X_{\max}(\alpha,i)) - CVaR_{1-\xi}(L_1(X_{\max}(\alpha,i)))\}$;

   (c) $MinDMin^{\alpha} = \min_i \{L_1(X_{\min}(\alpha,i)) - CVaR_{1-\xi}(L_1(X_{\min}(\alpha,i)))\}$;

   (d) $MinDMax^{\alpha} = \min_i \{L_1(X_{\max}(\alpha,i)) - CVaR_{1-\xi}(L_1(X_{\max}(\alpha,i)))\}$;

(e) $CADMin^{\alpha} = \frac{\sum_{i=1}^{i=3570} \left[L_1(X_{\min}(\alpha,i)) - CVaR_{1-\xi}(L_1(X_{\min}(\alpha,i)))\right]}{3570}$;

(f) $CADMax^{\alpha} = \frac{\sum_{i=1}^{i=3570} \left[L_1(X_{\max}(\alpha,i)) - CVaR_{1-\xi}(L_1(X_{\max}(\alpha,i)))\right]}{3570}$.

The maximum amount that the investors may loose, in the best and worst case, for any α, in our experiments, is: $MaxDMin^{10\%} = 3,870.924$; $MaxDMin^{15\%} = 3,883.596$; $MaxDMin^{85\%} = 4,061.01$; $MaxDMax^{10\%} = 3,813.143$; $MaxDMax^{15\%} = 3,825.905$; and $MaxDMax^{85\%} = 4,004.576$ in millions of dollars. This is for policy scenarios in which bioethanol is blended with gasoline. Therefore, we learn that the SCOSC is susceptible to a huge loss of expected profit whenever the Blend Wall increases. The amount that the investors may loose, for different α, in the best and worst case is:

- $MinDMin^{10\%} = 3,754.679$ and $MinDMin^{15\%} = 3,719.816$;
- $MinDMin^{85\%} = 3,353.65$ and $MinDMax^{10\%} = 3,692.529$;
- $MinDMax^{15\%} = 3,658.03$; and $MinDMax^{85\%} = 3,308.987$;

in millions of dollars. Similarly, the lost average expected profit is: $CADMin^{10\%} = 3,778.278$; $CADMin^{15\%} = 3,755.654$; $CADMin^{85\%} = 3,604.026$; $CADMax^{10\%} = 3,717.798$; $CADMax^{15\%} = 3,695.319$; and $CADMax^{85\%} = 3558.78$ in millions of dollars.

Another difference between the risk averse approach and the risk neutral approach is that RFS2 plays a crucial role in the expected profit that investors may gain in the risk averse approach, in contrast to the risk neutral approach. Therefore, it may be a good idea to make prudent decisions while creating the SCOSC, so that it is robust against policy changes and can withstand the economic crises; we recommended some robust strategic investment decisions to investors in Section 7.5.4.

2. *Environment Perspective* – During economic crises as opposed to a normal situation: (1) the amount of bioethanol blended with gasoline is sensitive to RFS2 changes; (2) many intermediate blends are are produced to increase the expected profit; and (3) the SCOSC requires government subsidy for blending bioethanol with gasoline and remains environmentally friendly, at least $TCI \geq 0.81 \ \frac{\$}{\text{gal}}$ tax credit for foreign bioethanol blended with gasoline, or at least $TCL \geq 0.009 \ \frac{\$}{\text{gal}}$ tax credit for US bioethanol blended with gasoline. Considering energy security and supporting local industries, we recommend 0.009 $\frac{\$}{\text{gal}}$ tax credit for US bioethanol blended with gasoline.

3. *Social and Managerial Perspective* – The RFS2 influences the expected number of jobs created within the economic crises, in contrast to a regular economic situation. Setting up a bio-refinery with capacity $238,800 \ \frac{MT}{\text{y}}$ at: Adams, Butler, Chase, Custer, Fillmore, Gage, Hall, Howard, Jefferson, Kearney, Keith, and Seward counties remains a resilient decision during economic crises too, whenever at least 0.135 and 0.171 $\frac{\$}{\text{gal}}$ tariff for foreign and US bioethanol blended with gasoline is considered. Under this condition no bioethanol is blended with gasoline. This implies the capacity of the bio-refineries are used for export, which can be utilized for other purposes, e.g., combating with COVID-19 by helping towards producing sanitizers. Establishing a blending site at Sarpy county with capacity 109.77 $\frac{M\text{gal}}{\text{y}}$ remains a resilient decision during economic crises too, if $(\eta, \theta) \in A$, see Section 7.5.4.2.

7.7 Conclusions and Further Research

We studied the Sustainable Crude Oil Supply Chains (SCOSCs) created in response to the US government policies: Renewable Fuel Standard 2 (RFS2), Tax Credits for US and foreign bioethanol blended with gasoline (TCL and TCI respectively), Tariffs for US and foreign bioethanol blended with gasoline (TL and TI respectively), and Blend Wall (BW), during economic crises, e.g., COVID-19, by employing a Conditional Value-at-Risk (CVaR) approach. This is to protect the investments in the SCOSC against financial risks during economic catastrophes. To that end, we extend the research performed by Ghahremanlou and Kubiak (2020a), which considers existing and 1^{st} and 2^{nd} generation bio-refineries, refineries and gasoline importers, exporters and importers of 1^{st} and 2^{nd} generation bioethanol, blending sites, and distribution centers. We proposed a two-stage stochastic programming model including two objective functions: the CVaR of annual expected profit maximization to study economic perspective, and the expected number of jobs created during the 30 year lifetime of the project to evaluate the social perspective of the SPSC within a state of the US. We learn that:

- Whenever the US or foreign bioethanol are blended with gasoline, respectively $TCL \geq 0.009 \frac{\$}{\text{gal}}$ or $TCI \geq 0.81 \frac{\$}{\text{gal}}$, for fixed TCL, TCI, TL, TI, and RFS2, by increasing the BW: (1) the CVaR of annual expected profit increases; (2) more environmentally friendly fuel is produced; and (3) the expected number of jobs created may increase. Since Environmental and Energy Study Institute (2014) reports 80% of the vehicles are able to consume up to 15% bioethanol in their fuel in 2014, we recommend pushing the BW to 15%. Another method could be mandating the registration of only Flex-Fuel Vehicles, which permits increasing the BW to 85%.

- For fixed TCL, TCI, TL, TI, and BW, by increasing RFS2: (1) the CVaR of annual expected profit reduces; (2) may increase the amount of bioethanol blended with gasoline, if Tax Credit for local bioethanol blended with gasoline is at least $TCL \geq 0.009 \frac{\$}{\text{gal}}$, or Tax Credit for foreign ethanol blended with gasoline is at least $TCI \geq 0.81 \frac{\$}{\text{gal}}$; (3) may influence the expected number of jobs created, and the number of bio-refineries and blending sites.

- For fixed RFS2, TCI, TI, and BW, by increasing $TCL \geq 0.009\ \frac{\$}{\text{gal}}$: (1) the CVaR of annual expected profit increases; (2) more environmentally friendly fuel may be produced; (3) the expected number of jobs created may increase. In contrast, for fixed RFS2, TCI, TI, and BW, by increasing TL: (1) the CVaR of annual expected profit stays the same; (2) environmentally friendly fuel receives no impact; (3) the expected number of jobs created may reduce.

- For fixed RFS2, TCL, TL, and BW, by increasing $TCI \geq 0.81\ \frac{\$}{\text{gal}}$: (1) the CVaR of annual expected profit increases; (2) more environmentally friendly fuel is produced; (3) the expected number of jobs created may increase. In contrast, for fixed RFS2, TCL, TL, and BW, by increasing TI: (1) the CVaR of annual expected profit stays the same; (2) environmentally friendly fuel may be produced; (3) the expected number of jobs created may stay the same.

We conclude that for businesses to remain feasible, and produce the most environmentally friendly fuel, a minimum $TCI \geq 0.81$ and $TCL \geq 0.009\ \frac{\$}{\text{gal}}$ tax credit for foreign and US bioethanol blended with gasoline should be considered. This will result in Nebraska being dependent on foreign bioethanol. To make Nebraska independent from foreign bioethanol, at least a $TI \geq 0.135\ \frac{\$}{\text{gal}}$ tariff for foreign bioethanol blended with gasoline must be considered along with $TCL \geq 0.009\ \frac{\$}{\text{gal}}$ tax credit for foreign and US bioethanol blended with gasoline.

We observed that by maintaining at least $TL \geq 0.171\ \frac{\$}{\text{gal}}$ and $TI \geq 0.205\ \frac{\$}{\text{gal}}$ Tariffs for US bioethanol and foreign bioethanol blended with gasoline, respectively, bioethanol is not blended with gasoline, although bio-refineries are producing bioethanol for export. Under these policy conditions, the capacity of bio-refineries can be utilized for producing ethanol[2] to be used for producing sanitizers to fight COVID-19; it also may be a solution for the fallen demand of bioethanol due to the 2020 Saudi Arabia-Russia Oil Price War and COVID-19. Additionally, this might be an initial step for moving toward introducing other transportation fuels, e.g., hydrogen or electricity.

We learned in the risk averse situation, which is a general preference during the economic crises, such as the one which is currently created by COVID-19 and the Price War, RFS2 plays an important role in the SCOSC, in contrast to the neutral economic condition, studied by Ghahremanlou and Kubiak (2020b). Additionally, we observed the importance of BW, TCL, TL, TCI, and TI policies for the SCOSC.

The bankruptcy of Philadelphia Energy Solutions, blaming RFS2, revealed the significance of creating robust SCOSCs against policy changes, since government policies may not be always beneficial to all the SCOSCs in the current complex market. For at least 0.135 and 0.171 $\frac{\$}{\text{gal}}$ tariff for foreign and US bioethanol blended with gasoline, setting up a bio-refinery with capacity $238,800\ \frac{MT}{\text{y}}$ at: Adams, Butler, Chase, Custer, Fillmore, Gage, Hall, Howard, Jefferson, Kearney, Keith, and Seward counties is a robust investment decision. Additionally, establishing a blending site at Sarpy county with capacity 109.77 $\frac{M\text{gal}}{\text{y}}$ is robust too, if at least 0.171 $\frac{\$}{\text{gal}}$ tariff for US bioethanol blended with gasoline is considered. A further key observation is that it proves to be a resilient strategic decision for investors to set up bio-refineries and blending sites even in times of economic crises.

Employing the mathematical programming model developed in this paper, and repeating this study for different levels of risk aversion is an avenue to explore. Conducting this study for other states of US may lead to new insights due to the inherent variances occurring in different geographical regions, thus is another direction for further research. Using other risk approaches, e.g., semideviation, see Ahmed (2006) or excess probability, see Schultz

[2] We reference ethanol as an ingredient in sanitizers, which require a higher grade of alcohol relative to bioethanol as a fuel additive.

and Tiedemann (2003), are other research directions.

Chapter 8

Conclusions

We studied Sustainable Petroleum Supply Chains (SPSCs) created as a result of the US government policies: Renewable Fuel Standard 2 (RFS2), Blend Wall (BW), Tax Credits for US and foreign bioethanol blended with gasoline (TCL and TCI respectively), and Tariffs for US and foreign bioethanol blended with gasoline (TL and TI respectively). These policies led to the creation of Bioethanol Supply Chains (BSCs) and to the merger with Conventional Petroleum Supply Chains (CPSCs) to form SPSCs. This has been considered as the best solution for combating global warming and becoming energy independent. The priority of the US as the largest global oil producer and consumer has made it the focus of this thesis, including six main chapters, Chapters 2 – 7, formed by six papers, two of which are in press, three of which are under review, and one paper is to be submitted.

These six papers or chapters discussed two different SPSCs:

1. The first three papers correspond to Chapters 2, 3, and 4, and were devoted to the creation of the most environmentally friendly SPSC. This accounts for the most environmentally friendly bioethanol developed so far, 2^{nd} generation bioethanol. Creating this SPSC in the 23 states which do not have any bio-refinery in place would require minimum infrastructural change. In Chapter 2 we developed the risk neu-

tral mathematical programming models, General Model (GM) and the Lean Model (LM); the latter is an approach to overcome the computational complexity of the GM. We performed a case study including computational experiments by employing the LM in Chapter 3 for the State of Nebraska. Chapter 4 proposed a risk averse mathematical programming model and applied it for computational experiments in a case study for the State of Nebraska. Sections 2.4, 3.5, and 4.7 provided conclusions and further research directions for these chapters. In these sections we provided recommendations for the government and investors. Furthermore, in Section 4.6, we compared the results of the risk averse model case study in Chapter 4 with the results of the risk neutral model case study in Chapter 3. This comparison better clarified the importance of each model, and as well it provided some strategic investment decision recommendations resilient to risk preferences, both neutral and averse. The comparison showed the SPSC with risk averse model as compared to the SPSC with risk neutral model:

(a) made at least $7,553.004$ and at most $18,209.965$ million dollars less expected profit in our experiments;

(b) required a great deal of subsidy, e.g., about 12 times higher level of TCL to create the SPSC for the BW equal to 15%;

(c) resulted in a portfolio of blends, e.g., 0, 8.7%, 9.2%, 10%, 12.4%, 13.2%, 15%, 70.1%, 70.9%, 85%. This implies the SPSC with the risk averse model is very sensitive to policy change;

(d) stopped blending bioethanol with gasoline at approximately six times lower levels of TI and TL;

(e) reduced or maintained the total number and capacity of bio-refineries and blending sites for any BW value.

However, there were some common strategic decision recommendations in the SPSC, which are insensitive to policy change, transportation cost, and risk preferences:

(a) *Bio-refineries* – Setting up a bio-refinery in Hall county that could process the amount of corn stover from $772,151.89$ to $2,316,455.67$ $\frac{MT}{\text{y}}$ to produce 2^{nd} generation bioethanol, for the BW equal to 10% and 15%, if $TCL \geq 0.189$ $\frac{\$}{\text{gal}}$; establishing a bio-refinery in York, Buffalo, and Hall counties that could process the amount of corn stover from $772,151.89$ to $2,316,455.67$ $\frac{MT}{\text{y}}$ to produce 2^{nd} generation bioethanol, for the BW equal to 85% and $TCL \geq 0.189$ $\frac{\$}{\text{gal}}$;

(b) *Blending sites* – Establishing a blending site in Douglas county that could deliver the amount of fuel from 182.95 to 402.49 $\frac{M\text{gal}}{\text{y}}$, for the BW equal to 10% and 15%, if $TCL \geq 0.189$ $\frac{\$}{\text{gal}}$.

2. The last three papers formed Chapters 5, 6, and 7 respectively and focused on the creation of the SPSC in the 27 states with bio-refineries already in place. The SPSC included all existing infrastructures, 1^{st} and 2^{nd} generation bioethanol, and their imports and exports. Since this SPSC is an extension to the one in Chapters 2, 3, and 4, we called the developed risk neutral models Extended General Model (EGM) and Extended Lean Model (ELM) in Chapter 5. By employing the ELM, we conducted a case study including computational experiments in Chapter 6 for the State of Nebraska. We converted the risk neutral model to a risk averse model, and performed a case study consisting of computational experiments in Chapter 7 for the State of Nebraska. Chapters 5, 6, and 7 have their own conclusions and research directions which can be found in Sections 5.4, 6.5, and 7.7. We provided recommendations for the government and industry in these sections. Furthermore, in Section 7.6, the results of both case studies, those in Chapter 6 and Chapter 7 are compared, to highlight the significance of developing risk neutral and risk averse models and

provide resilient strategic investment decision recommendations to withstand both risk preferences. The comparison demonstrated the SPSC with the risk averse model as compared to the SPSC with the risk neutral model:

(a) generated at least $3,308.987$ and at most $4,061.01$ million dollars less expected profit in our experiments. The difference $4,061.01 - 3,308.987 = 752.023$ million dollars for this SPSC is less in comparison to $18,209.965 - 7,553.004 = 10,656.961$ million dollars for the most environmentally friendly SPSC in item number 1(a) in this chapter. This implies that investment for creating the SPSC, including existing bio-refineries and 1^{st} generation bioethanol, involves less financial risk;

(b) required at least $TCI \geq 0.81\ \frac{\$}{\text{gal}}$ or at least $TCL \geq 0.009\ \frac{\$}{\text{gal}}$ more subsidy to be created;

(c) resulted in a portfolio of blends, e.g., 0, 9.8%, 9.9%, 10%, 14.7%, 14.9%, 15%, 82.1%, 84.1%, 84.9%, 85%. This implies the SPSC with the risk averse model is very sensitive to policy change;

(d) stopped blending bioethanol with gasoline at approximately three times lower levels of TL and TI;

(e) reduced or maintained the total number and capacity of bio-refineries and blending sites, for any BW value.

Moreover, the comparison revealed some common strategic decision recommendations in the SPSC, which are insensitive to policy change, transportation cost, and risk preferences:

(a) *Bio-refineries* – Setting up a bio-refinery in Adams, Butler, Chase, Custer, Fillmore, Gage, Hall, Howard, Jefferson, Kearney, Keith, and Seward counties with capacity $238,800\ \frac{MT}{\text{y}}$ to produce 1^{st} generation bioethanol, for $TI \geq 0.135\ \frac{\$}{\text{gal}}$ and $TL \geq 0.171\ \frac{\$}{\text{gal}}$;

(b) *Blending sites* – Establishing a blending site in Sarpy county with capacity 109.77 $\frac{M\text{gal}}{\text{y}}$, for $TL \geq 0.171\ \frac{\$}{\text{gal}}$.

Splitting Chapters 2 – 7 into two classes aimed to increase the focus on each SPSC; the SPSC without existing infrastructures and the SPSC with existing infrastructures. This revealed the changes to each SPSC with varying risk preferences in terms of policies, locations and capacities of bio-refineries and blending sites. To provide cross-SPSC insights, we further categorize Chapters 2 – 7 into two classes based on their primary focus on either theory or applications: (1) Chapters 2 and 5 focused on solution techniques, and (2) Chapters 3, 4, 6, and 7 conducted case studies. This type of classification leads to the following universal findings:

- Chapters 2 and 5 revealed the current inability of existing optimization algorithms to efficiently solve GMs to optimality, more precisely the inability to solve both deterministic and stochastic multi-echelon location-allocation problems in reasonable time.

- Chapters 3, 4, 6, and 7 studied SPSCs created in response to government policies by conducting case studies for the State of Nebraska, including computational experiments. The universal findings for the SPSCs are as follows:

  1. The policies (BW, RFS2, TCL, TCI, TL, and TI) have a positive impact on three aspects of the SPSCs: the economic aspect, by increasing the expected profit; the environmental aspect, by increasing the amount of bioethanol blended with gasoline; and the social aspect, by increasing the expected number of jobs created. According to this the impact of each policy on each aspect is as follows:

(a) Economic aspect – Increasing the BW has a positive impact on this aspect whenever bioethanol is blended with gasoline, which occurs for $TCL \geq 0.009 \ \frac{\$}{\text{gal}}$ or $TCI \geq 0.81 \ \frac{\$}{\text{gal}}$. The interval for the TCL is the intersection of (1) $TCL \geq 0.009$, (2) $TCL \geq 0.009$, (3) $TL \leq 0.351$, and (4) $TCL \geq 0.009 \ \frac{\$}{\text{gal}}$, see Sections 3.5, 4.7, 6.5, and 7.7. Note that $TCL \geq 0.009$ meets the condition $TL \leq 0.351$, thus the intersection of both is $TCL \geq 0.009$. This interval for TCI is the intersection of (1) $TI \leq 1.285$, (2) $TCI \geq 0.01$, (3) $TI \leq 0.135$, and (4) $TCI \geq 0.81 \ \frac{\$}{\text{gal}}$; their intersection simplifies to $TI \leq 0.135$ and $TCI \geq 0.81$. Note again that $TCI \geq 0.81$ satisfies the condition $TI \leq 0.135$, thus the intersection of both is $TCI \geq 0.81$. Increasing TCL has its positive impact whenever US bioethanol is blended with gasoline, which takes place for $TCL \geq 0.009 \ \frac{\$}{\text{gal}}$. Increasing TCI has its positive impact whenever foreign bioethanol is blended with gasoline, which happens for $TCI \geq 0.81 \ \frac{\$}{\text{gal}}$. In contrast, an increase in RFS2, TL, or TI has a negative impact on this aspect, and may result in bankruptcy of the SPSCs. The RFS2 negative impact is neutralized in the risk neutral model, whenever 1^{st} generation bioethanol is produced, see Section 6.5. The negative impact of TL or TI occurs if $TL \leq 0.351 \ \frac{\$}{\text{gal}}$ or $TI \leq 0.135 \ \frac{\$}{\text{gal}}$ respectively. Increasing TL in range $[0, 0.351] \ \frac{\$}{\text{gal}}$ or TI in range $[0, 0.135] \ \frac{\$}{\text{gal}}$ respectively reduces the amount of US or foreign bioethanol blended with gasoline. Note that a subsidy of $TCL \geq 2.151 \ \frac{\$}{\text{gal}}$ is enough for the creation of SPSCs, regardless of any other policies and risk preferences, except in one case; in the risk averse model, if the BW is equal to 10%, the $TCL = 2.151 \ \frac{\$}{\text{gal}}$ is not enough for creating the most environmentally friendly SPSC, see Section 4.5.1. To reduce the subsidy and reallocate budget to other priorities, we recommend increasing the BW by registering only flex-fuel vehicles.

(b) Environmental aspect – Generally an increase in BW, RFS2, TCL, or TCI has a positive impact on this aspect. The BW or RFS2 has its positive impact if bioethanol is blended with gasoline, which occurs for $TCL \geq 0.009 \frac{\$}{\text{gal}}$ or $TCI \geq 0.81 \frac{\$}{\text{gal}}$. However, RFS2 does not impact this aspect in risk neutral models. The positive impact of TCL or TCI takes place if $TCL \geq 0.009 \frac{\$}{\text{gal}}$ or $TCI \geq 0.81 \frac{\$}{\text{gal}}$ respectively. Contrary to this, raising TL or TI has a negative impact on this aspect if $TL \leq 0.351 \frac{\$}{\text{gal}}$ or $TI \leq 0.135 \frac{\$}{\text{gal}}$ respectively. The amount of US or foreign bioethanol blended with gasoline drops by increasing TL in range $[0, 0.351] \frac{\$}{\text{gal}}$ or TI in range $[0, 0.135] \frac{\$}{\text{gal}}$ respectively. Note that if $TCL \geq 2.151 \frac{\$}{\text{gal}}$ and $TI \geq 0.205 \frac{\$}{\text{gal}}$, then the SPSCs produce the most environmentally friendly fuel, and the State is fully independent from foreign bioethanol.

(c) Social aspect – Raising the BW has a positive impact whenever bioethanol is blended with gasoline, which takes place for $TCL \geq 0.009 \frac{\$}{\text{gal}}$ or $TCI \geq 0.81 \frac{\$}{\text{gal}}$. Increasing TCL has a positive impact on this aspect in risk neutral models for $TCL \geq 0.009 \frac{\$}{\text{gal}}$. Increasing RFS2 or TCI does not have any impact on this aspect in the SPSCs with risk neutral models. Increasing TL does not have a positive impact on this aspect as it discourages the blend of US bioethanol, and may result in US bioethanol production reduction.

2. Regardless of any other policies and risk preferences, $TCL \geq 2.151 \frac{\$}{\text{gal}}$ and $TI \geq 0.205 \frac{\$}{\text{gal}}$ result in the creation of SPSCs and production of the most environmentally friendly fuel in the State. This also results in the State being independent from foreign bioethanol. However, in the risk averse model the most environmentally friendly SPSC is not created for the BW equal to 10%

and $TCL = 2.151 \ \frac{\$}{\text{gal}}$, see Section 4.5.1.

3. $TL \geq 0.751 \ \frac{\$}{\text{gal}}$ and $TI \geq 1.685 \ \frac{\$}{\text{gal}}$ would stop the blending of bioethanol with gasoline, although the bio-refineries would produce bioethanol for export. These tariffs may help the government to utilize the capacity of US bio-refineries in combating COVID-19 by upgrading bioethanol to produce ethanol which is used as a main component in sanitizers. The new market for ethanol may be a good solution for rescuing bio-refineries from the fall in demand for bioethanol due to the 2020 Saudi Arabia-Russia Oil Price War and COVID-19; this is a promising avenue for further research. Moreover, if government wants to introduce new transportation energies, e.g., solar or hydrogen, these tariffs would align the market accordingly.

Finally, we concluded our findings concisely in this chapter, although readers can refer to the corresponding sections in Chapters 2 – 7 for further details.

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