DEVELOPMENT OF A QUANTITATIVE RISK ANALYSIS APPROACH TO EVALUATE THE ECONOMIC PERFORMANCE OF AN INDUSTRIAL-SCALE BIOREFINERY

by

Max (Yu Max) Wang

B.A.Sc., The University of British Columbia, 2007
M.A.Sc., The University of British Columbia, 2010

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF
THE REQUIREMENTS FOR THE DEGREE OF

DOCTOR OF PHILOSOPHY

in

THE FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES
(Chemical and Biological Engineering)

THE UNIVERSITY OF BRITISH COLUMBIA
(VANCOUVER)

August, 2018

Committee

submitted by Yu Wang in partial fulfillment of the requirements for

the degree of Doctor of Philosophy

in Chemical Engineering

Examining Committee:

Anthony Lau, Chemical and Biological Engineering

Co-supervisor

Shahab Sokhansanj, Chemical and Biological Engineering

Co-supervisor

Fariborz Taghipour, Chemical and Biological Engineering

University Examiner

Gary Bull, Forestry

University Examiner

Additional Supervisory Committee Members:

Jim Lim, Chemical and Biological Engineering

Supervisory Committee Member

Hisham Zerriffi, Forestry

Supervisory Committee Member

Abstract

The overall objective of this dissertation was to evaluate the economic performance of a commercial-scale biorefinery given the volatility in the market price of the final product and the variability in the biomass delivered cost. To this end, a risk analysis methodology comprised of five steps was developed: 1) construct the supply area geographical data base, 2) perform Monte Carlo simulation via the Integrated Biomass Supply Analysis and Logistics Multi-Crop model (IBSAL-MC) to produce the biomass delivered cost distribution, 3) conduct economic analysis by combining the biomass delivered cost distribution with the product market price to generate a ROI (return on investment) heat map, 4) repeat Steps 1 to 3 for an alternative scenario and 5) compare heat maps from different scenarios to quantify the effectiveness and incentive available for achieving an alternative scenario.

The proposed methodology was applied to a cellulosic sugar plant under construction in Southwestern Ontario, Canada. Three biorefinery scenarios were considered including small-scale (175 dry tonnes (dt)/day), medium-scale (520 dt/day) and large-scale (860 dt/day). Results showed that the magnitude of the required logistical resources and their associated upfront and administrative costs hindered the biorefinery's economic performance as its scale increased.

The risk analysis approach was then applied to the small-scale scenario. Potential economic incentives for participating biomass producers were quantified as the participation rate increased from 20% to 30%, 40% and 50. While increasing farm participation rate was economically beneficial to the biorefinery, there were more economic benefits if the sugar market price was in a favourable range. When a farmers' co-operative was introduced to the supply system, if the biorefinery could secure a long-term consumer of the produced sugar in the price range of $425-575/tonne, the farmers' co-operative and other investors of the biomass project were both more likely to achieve an acceptable annual ROI that exceeds 10%.

Lay Summary

The overall objective of this dissertation was to evaluate the economic performance of a commercial-scale biorefinery given the volatility in the market price of the final product and the variability in the biomass delivered cost. The outcome of the economic performance and risk analysis can be used to facilitate and promote the discussion on the development of risk mitigation strategies and business relationship between biorefineries and biomass producers.

The proposed methodology was applied to a cellulosic sugar plant under construction in Southwestern Ontario, Canada. Results showed that the magnitude of the required logistical resources and their associated upfront and administrative costs hindered the biorefinery's economic performance as its scale increased. It was also concluded that while increasing farm participation rate is economically beneficial to the biorefinery, there were more economic benefits if the sugar market price was in a favourable range.

Preface

This Ph.D. dissertation is divided into seven chapters and four appendices. The author, Yu Wang, has done all the literature review, planning the approach, simulation trials, data processing and analysis and preparation of manuscript. The research was conducted under the supervision of Professors Shahab Sokhansanj and Anthony Lau in the Department of Chemical and Biological Engineering at the University of British Columbia. The author received considerable guidance from Dr. Mahmood Ebadian, UBC-BBRG Research Associate and expert in supply logistics modeling. The co-authors contributed to the published papers and the scientific content of the manuscripts are members of the Biomass and Bioenergy Research Group (BBRG) and Dr. Hisham Zerriffi from the Forestry Department at the University of British Columbia. A version of Chapter 4 and 5 of this dissertation is published in peer-reviewed journals as follows:

Journal Publication

Wang, Y., Ebadian, M., Sokhansanj, S., Webb, E. and Lau, A. 2017. Impact of the biorefinery size on the logistics of corn stover supply – A scenario analysis. Applied Energy 198: 360-376.

Wang, Y., Ebadian, M., Sokhansanj, S., Webb, E., Zerriffi, H. and Lau, A. 2018. A novel risk analysis methodology to evaluate the economic performance of a biorefinery and to quantify the economic incentives for participating biomass producers. Biofuels, Bioproducts and Biorefining. doi:10.1002/bbb.1862

Table of Contents

List of Tables

List of Figures

List of Symbols

C	capital investment, $
db	dry bulb
dt	dry tonne
E_a	achieved economic benefit, $
E_P	total economic incentive provided, $
E_T	total economic benefit, $
n	number of years
P_i	probability of event i
R	expected annual ROI
R_0	expected annual ROI for the base case scenario
R_a	adjusted expected annual ROI
R_i	expected annual ROI for the alternative scenario
T_{Fixed}	fixed transportation cost coefficient, $/tonne
$T_{Variable}$	variable transportation cost coefficient, $/tonne/km
wb	wet bulb

BIC	Bioindustrial Innovation Canada Inc.
CSPC	the Cellulosic Sugar Producers Cooperative Inc.
FF	farm-firm
FCF	farm-co-operative-firm
IBSAL-MC	the Integrated Biomass Supply Analysis and Logistics Multi-Crop model
IRR	internal rate of return
NPV	net present value
OMAFRA	Ontario’s Ministry of Agriculture
ROI	return on investment
SCDR	supply chain disruption risk
SCOR	supply chain operational risk

Acknowledgements

The preparation of this thesis would not have been possible without the support and guidance of my Ph.D. supervisors, Professor Shahab Sokhansanj and Anthony Lau. Their encouragement and insights enabled me to develop an understanding of the subject and to complete this thesis. Specifically, I would like to acknowledge the great help I received from Dr. Mahmood Ebadian in modeling of the supply logistics. Mahmood devoted many hours of his valuable time and expertise in the development of discussions around risk analysis.

I would also like to express my gratitude to another member of my supervisory committee, Dr. Hisham Zerriffi, for his extreme helpful ideas and suggestions for improving the work presented in this dissertation. I am also grateful to another member of my supervisory committee, Dr. Jim Lim, for his excellent advices and time dedication.

My gratitude also goes to members from AGCO, BIC and CSPC for their experienced, practical and insightful discussion. I also express my deepest appreciation to the financial support received from Biofuel Network of Canada and BBRG (UBC Biomass and Bio Energy Research Group).

Dedication

To my wife, Luwen, for her love, understanding and support.

Chapter 1. Introduction

1.1 Background

Emissions of anthropogenic CO_2 and other greenhouse gases (GHG) have become arguably one of mankind's greatest environmental problems that have caused global warming and climate change. Some advocated that the development of biomass industry might be able to help mitigate the problem by producing biofuel and bio-chemical from biomass (first generation) and waste biomass (second generation) (Leboreiro & Hilaly, 2013; Yue et al., 2013). From the sustainability perspective, the products derived from biomass are generally considered to be carbon neutral (Sultana et al., 2010; Theerarattananoon et al, 2011; Giuntoli et al., 2013) under the assumption that the production performance and emission control are efficient during the time frame of analysis (Gnanasounou et al., 2009). As a result, bioenergy and bio-chemicals production can help mitigate greenhouse gas emissions. From the security and politics perspective, using domestically produced biomass-derived energy and chemicals can mediate the security and economic concerns of importing products derived from fossil fuels at the turbulent international market price (Dien et al, 2006; Hettinga et al., 2009; Theerarattananoon et al, 2011). Finally, from the community and society development perspective, local biomass energy and chemical production provides substantial socio-economic benefits (Miranda et al., 2015), such as promoting regional development and creating jobs and income in rural areas (Elghali et al., 2007).

However, these benefits associated with the development of biomass industry is not without controversies. The environmental benefits from using bio-ethanol as fuel in comparison to fossil fuel may be ambiguous according to a life-cycle analysis conducted by von Blottnitz and Curran (2007). There is also a lack of a consensual metric for determining whether replacing fossil fuel with biofuel is sustainable or not (Bosch et al., 2015). Criticisms also arise from competing arable land use between biomass production for food and energy (Smeets et al., 2006; Mohr et al., 2016). In some developing countries, the cultivation of energy crops can aggravate water shortage, food shortage and fuel poverty since the energy crops are commodities for exportation to the industrialized world (Gerbens-Leenes et al., 2009; Gold & Seuring, 2011). In addition, waste biomass, such as corn stover and wheat straw, provide important ecosystem services, such as protection against wind and water erosion, increasing infiltration and water retention, provision of soil carbon and cycling of many nutrients (Karlen et al., 2014). The long-term impacts of the removal of waste biomass requires more study (Mann et al., 2002).

While the extend of the benefits associated with biomass projects remains debatable, the importance of conducting systematic analysis and optimization of biomass supply chain system to enhance the benefits and to reduce the challenges of biomass projects has been acknowledged in the literature (Sultana et al., 2010; Gold & Seuring, 2011; Li et al., 2012; Yue et al., 2014; Abbati de Assis et al., 2017). These considerations confirm the relevance of this study to the long-term economic success of industrial scale biomass projects.

1.2 Motivation

Despite the potential economic, social and environmental benefits associated with biomass projects, the development of industrial scale biorefineries has been hindered by risks arising from technical and non-technical obstacles (Elghali et al., 2007; Sultana et al., 2010; Giuntoili et al., 2013; Arnold & Yildiz, 2015; Miranda et al., 2015). Among non-technical barriers, biomass supply security (quantity, quality and unit price) and market prices of the products accounts for the highest risks (Yue et al., 2014; Abbati de Assis et al., 2017).

On the supply side, despite the seemingly abundant availability of crop residue (Sokhansanj et al., 2006a; Li et al., 2012), the delivered cost of biomass represents a major component (up to 56%) of the total production cost associated with biomass processing (Tao et al., 2014), and the nature of crop residue (low bulk density, moderate moisture content and sensitivity to biological reaction) (Gold & Seuring, 2011; Yue et al., 2014) further complicates the supply chain logistics. On the market side, the produced bio-chemicals and bio-energy face competitions of similar products produced through traditional means. The fluctuating market price is among the primary parameters that impacts the economic viability of a biomass project (Abbati de Assis et al., 2017).

This study is motivated by the need of a systematic approach to quantify the long-term economic performance and risks of a biomass project while capturing the dynamic and stochastic nature of the crop residue supply chain logistics and the volatility in the product's market price. In addition, there is also a need to develop a communication tool for all parties involved in a biomass project to understand the economic risks involved and to evaluate whether a proposed risk mitigation strategy or business model is suitable to the biomass project or not.

1.3 Contributions and Objectives

The main objective of this dissertation is to quantify the economic performance of a commercial-scale biorefinery given the volatility in the market price of the final product and the variability in the biomass delivered cost. The approach developed in this thesis incorporates an integrated biomass supply chain model that simulates the corn stover's movement from corn field to the biorefinery, but it can also be applied to other biomass types. The specific objectives are to:

a. Construct a supply chain logistics model for harvesting, collecting, handling, storage and transportation of crop residues.
    i. Construct a local supply area data base
    ii. Quantify the impact of the biorefinery size on the logistics of corn stover supply.
b. Develop a risk analysis approach to quantify economic performance of the biorefinery.
    i. Quantify the economic risks and profits of a commercial biorefinery experiencing fluctuation in biomass supply costs and bio-product market price.
    ii. Quantify the potential economic incentive available for biomass producers to increase their participation rate.
    iii. Investigate the potential business opportunities for a farmers' co-operative in a commercial scale biomass project.
    iv. Facilitate and promote the discussion on the development of risk mitigation strategies and business relationship between biorefineries and biomass producers.

The systematic economic risk analysis approach developed in this study can be used as a tool to provide valuable insights on the long-term economic profits and risks for a commercial biomass/biorefinery project to interested parties, such as biomass producers, investors, governments, politicians, engineers, academics and financial institutions. The outcome of the analysis can facilitate the discussion on operational standards, risk mitigation strategies, business structures and policies among interested parties.

Chapter 2. Literature Review

2.1 Synopsis

A rich body of knowledge has been developed on modeling, analyzing and optimizing the performance of biomass supply chain in terms of the biomass delivered cost, but there is a lack of discussion on quantifying the economic benefits and risks of a biomass project experiencing fluctuations in biomass supply costs and bio-product market prices. In this chapter, relevant studies have been reviewed under three categories as shown in Figure 2.1. From the literature view, a knowledge gap was identified to highlight the contributions of this thesis study.

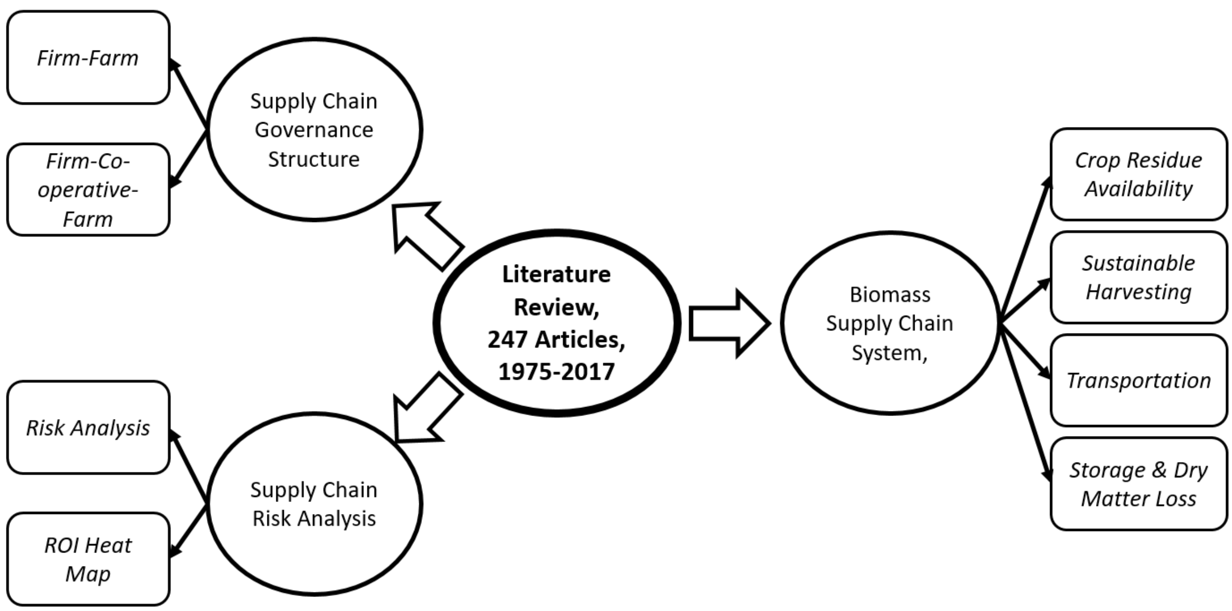


Figure 2. 1. Literature review summary

Researches done by Karlen et al. (2011), Jeschke and Heggenstaller (2012), Li et al. (2012), Duffy and Marchand (2013), Karlen et al. (2014) and Shah and Darr (2014) identified the critical components, such as grain yield, straw-to-grain ratio, sustainable harvesting, dry matter loss, transportation cost within a biomass supply chain system. Sokhansanj et al. (2006[a], 2006[b]), Kumar and Sokhansanj (2007), Hess et al. (2009), Nilsson et al. (2010), Stephen et al (2010), Zhang et al. (2012) and Ebadian et al. (2014) are examples of the studies that developed simulation models to evaluate biomass logistics operations. Goetschalckx et al. (2013), Chen et al. (2016) and Chiu & Choi (2016) all developed valuable discussion to reveal insights of the nature of risk and risk analysis. Golecha and Gan (2016a, 2016b) investigated the economic impact of business and partnership structure on biomass projects. Lastly, the logistics costs obtained through simulation are verified with those of Shah (2013), Martinez-Kawas (2013) and Duffy and Marchand (2013).

2.2 Biomass Supply Chain System

A literature review was conducted on the agriculture residue supply chain logistics system. Biomass supply chain plays a critical role in a biomass processing operation's economic feasibility and long-term success. The logistics must consider the biomass supply chain's seasonal nature and annual variability while it integrates time-sensitive biomass harvest, storage and delivery into one efficient and stable supply system that delivers high-quality biomass throughout the year until the next harvest season (Yue et al., 2013). In addition, the economic performance and risk analysis both need to consider the variances among the supply area and operation variables from one year to the next. As a result, the simulation of a biomass supply chain system can be very complex with a number of uncontrollable variables.

A typical bioenergy or bio-chemical production process (including the supply chain) consists of five stages: biomass harvest, upstream transportation, storage, processing and downstream transportation. For the purpose of this study, the supply chain system begins with harvesting corn stover at farms and ends with delivery to a processing facility's onsite storage. Within this supply chain system, the economic variable of interest is generally the biomass' delivered cost and the environmental variable of interest is usually the reduction of GHG emission. The delivered cost of biomass at the processing facility in \$/dry tonne (\$/dt) is the sum of harvesting cost, handling and transportation cost, storage cost and essential nutrient replacement cost. Table A1 provides a summary of the estimated crop residue harvesting, storage and essential nutrients replacement costs based on literature review. Considerable differences have been observed in machinery and labour costs (for instance, \$9.63-\$22.05/dt for wheat straw; \$16.6-\$36.3/dt for corn stover). Essential nutrients replacement cost also varies between \$18.60-\$57.39/dt for corn stover.

Due to agriculture activity and the time-sensitive nature of crop residue, the harvesting window for crop residue is usually a short period of time after grain harvest. During this time period, shredding, windrowing, baling and moving bales to storage all need to be completed.

Figure A1 provides an example of the grain and residue harvesting window for grain corn, winter wheat and soybean in Southern Ontario (McDonald, 2010). Yet in practice, the timing of the harvesting window depends on many additional factors, such as weather, soil condition, supplier's schedule and equipment and labor availability. A number of previous studies have been conducted to optimize the scheduling of machinery during the harvesting window. Duffy and Marchand (2013) examined the number of disc mowers, wheel rakes, balers and tractors required to harvest 250,000 tonnes of corn stover (with 10 hours per day operation) and the capital investment. POET's (2014) experiences suggest that baling should be done 24-48 hours after grain harvesting; and square balers are easier to transport and handle than round bales. Grooms (2014) reported that a third-party baling crew with Hiniker windrower shredders and Hesston & Challenger balers can harvest 2,500 high density bales (3' x 4' x 8') in one day.

2.2.1 Crop Residue Availability

In general, crop residue availability is estimated through multiplying grain yield, area cultivated and straw-to-grain ratio. The straw-to-grain ratio for corn is reported as 1.0 dry basis (Graham et al., 2007), 0.982-1.17 wet basis (Huang et al., 2012) and 1 wet basis (Li et al., 2012). The straw-to-grain ratio for wheat is reported as 0.8 wet basis (Weiser et al., 2014) and 1.1 wet basis (Sultana et al., 2010). The differences in this ratio for the same crop are mostly due to cultivation region, agricultural practices and crop species. Skott (2011) also suggested that the straw to grain ratio is reduced as more fertiliser is applied, but since the amount of fertiliser applied is set by regional norms, its impact is not likely to be significant in practice.

In addition to stover's availability, for biorefineries, another important characteristic is its chemical composition. Karlen et al. (2011) presented the average sugar and lignin concentrations in corn stover collected from 2005 to 2008 in central Iowa, as shown in Table A2. Although the overall sugar content from rotated corn is slightly lower than from continuous corn, it may be due to factors other than crop rotation, such as soil type, field slope and field moisture. Statistically, it is not significant enough to value stover from continuous corn over stover from rotated corn. For the purpose of analyzing biomass supply chain logistics, it is reasonable to assume that the corn stover chemical composition in the supply area meets the bio-processing facility's quality demand.

2.2.2 Sustainable Harvesting

Although very often crop residues are left in the field to rot (Sultana et al., 2010), they are not wasted because they provide important services to the soil's ecosystem. Mann et al. (2002) pointed out that studies are necessary in order to determine the long-term effects of stover harvest on erosion, water quality and soil organic carbon content. Jeschke and Heggenstaller (2012) reported that not every field is suitable for stover removal. They define sustainable stover harvesting as the removal of a portion of stover from the field leaving a sufficient amount behind to satisfy the needs of soil erosion mitigation, soil organic carbon maintenance and soil fertility management. They suggested that stover removal is ideally practiced in fields with excess residues that interferes with next year's agricultural activities, so partial stover harvest may improve corn yields and reduce corn production costs. Karlen et al. (2014) also suggested that crop residues have significant importance to many ecosystem services, such as protection against wind and water erosion, improving soil aggregation and structure, increasing infiltration and water retention, mitigating soil temperature fluctuations, provision of soil carbon and cycling of many nutrients.

Where crop residues are collected for use as animal feed and bedding, the nutrients eventually return to the field as manure (Karlen et al., 2015). It is generally recommended to partially remove crop residues and to apply additional fertilizers to cover the amount of essential nutrients removed. Through field research findings from 239 site-years at 36 sites in seven states in the U.S., Karlen et al. (2014) found that harvesting an average of 3.9 or 7.2 tonne stover per hectare from fields yielding 80 to 192 bu/ac can improve grain yield slightly at 57% and 51% of the sites respectively. The essential nutrients (N, P and K) removal for 3.9 and 7.2 tonne/ha stover removal are 24, 2.7 and 31 kg/ha and 47, 5.5 and 62 kg/ha respectively. Similarly, Shah and Darr (2014) estimated that 5.00 kg N, 1.99 kg P_2O_5 and 10.03 kg K_2O are removed per tonne of stover at 22% moisture content (wb).

In Iowa, DuPont (2015) recommended that corn stover harvest is most suitable on gently sloping (<= 4%) and productive (>= 180 bu/acre corn yield) fields managed with conservation or no-tillage. On such fields, they estimated about 1 dry ton of corn stover may be collected for every 42 bushels of grain (at 15.5% moisture content). The concept of sustainable partial removal of crop residue is attracting increasing attention and interests. Based on four years' soil test data from 7 POET-DSM stover harvest sites, Birrell et al (2014) concluded that with good soil and crop management, 1 tonne/ha of corn stover harvest should be sustainable, and in high corn yield fields (>200 bu/acre), it is possible to sustainably harvest even more stover. It is in agreement with values reported by other researchers. Jeschke and Heggenstaller (2012) suggested sustainable corn stover harvesting rate according to grain yield based on DuPont's practice in Iowa and recommendations, as shown in Table A3. The corn grain yield usually varies from one region to another. For the Southern Ontario region, Marchand's (2015) recommendations for sustainable removal of stover are slightly different (Table A4), when taking the impact of soil organic carbon content, erosion prevention, field slope and nutrients into consideration. For instance, it suggests 1.53 – 1.78 dt/ac corn stover can be sustainably harvested from fields with relatively high grain yield of 180 – 200 bu/ac.

2.2.3 Transportation

The cost of transporting baled crop residue from field side storage to other storage sites is an important component of the supply chain logistics. In general, it is made up of two components - fixed transportation cost and variable transportation cost as follows:

$$Trans_{Total} = Mass_{Total}(T_{Fixed} + T_{Variable}Distance) \quad \text{Eq. 1.1}$$

where $Trans_{Total}$ is the total transportation cost in \$, $Mass_{Total}$ is the total amount of biomass transported in tonne, T_{Fixed} is the fixed transportation cost coefficient in \$/tonne, $T_{Variable}$ is the variable transportation cost coefficient in \$/tonne/km and Distance is the total distance of transportation in km. Table A5 provides a summary of the values of the fixed and variable transportation cost coefficients obtained from literature review. Although railway and barge transportation have lower variable transportation cost coefficients, their fixed cost transportation coefficients are significantly higher than those of trucking. As a result, trucking is generally considered as the most suitable means of transportation for crop residues (Arctic Energy Alliance, 2009; Mupondwa et al., 2012; Roni et al., 2014).

It is possible to have an unexpected significant decrease in regional biomass supply due to natural disasters, transporting biomass from distance suppliers may be one option to mitigate the risk associated with biomass supply security. For example, in Canada, a large number of empty railcars have to be moved from the west coast to the east coast caused by the imbalanced exports and imports between Canada and China, the actual railway cost of biomass transportation may not be as high if estimation is based on the coefficients in Table A5. It has been noticed that

Ontario's mushroom industry is currently transporting the straws from the Canadian Prairies via railway, and the delivery price is competitive with local biomass' delivery price.

The abstract concept of "supply radius" is commonly used in both strategic-scale and operational-scale supply chain logistics analysis. Nguyen and Prince's study (1996) showed that crop residue's delivered cost is a function of the supply area radius. However, unlike traditional chemical plants, bio-energy and bio-chemical processing facilities' total production cost does not necessarily decrease with increasing producing capacities. The amount of biomass available can be considered as proportional to arable land area and thus the square of supply radius. Yet, the transportation cost can be considered as proportional to the cubic of supply radius. As a result, with increasing supply radius, the increment in the transportation cost will eventually outweigh the reduction in the biomass production cost. A number of studies (for instance, Leduc et al., 2010; Sultana et al., 2010; Leboreiro & Hilaly, 2013) also illustrated that although the facility's scale factor favours a large output capacity. The increase in the cost of transporting biomass to the facility limits the capacity to an optimal value where the total production cost is minimized.

For supply chain logistics analysis, two additional variables are introduced to relate the supply radius to the actual distance traveled during upstream transportation. The first variable is the ratio of "the average straight-line distances between points in the supply area" to "the centre of the supply area" and it is often assumed to be 2/3 (i.e. 0.67) (Nilsson et al., 2010; Sultana et al., 2010; Mupondwa et al., 2012). The second variable is the ratio of "the distance of the actual routes" to "the average straight-line distance", which is commonly known as winding factor or tortuosity. For rural agricultural regions in developed countries, it is estimated to be 1.3 -1.4 (Nilsson et al., 2010; Sultana et al., 2010). However, if all the distances between each biomass supplier and the processing facility are known, supply radius is no longer necessary for the analysis, rather it can be estimated afterwards based on the distribution of biomass suppliers for the purposes of comparison and illustration.

2.2.4 Storage and Dry Matter Loss

Biomass storage is a necessary part of the supply chain in order to ensure sufficient feedstock for a biorefinery's year-round operation. Under conventional biomass storage management, crop residue will lose dry matter and have deterioration in quality as a result of natural biological decomposition (Gold & Seuring, 2011; Shah & Darr, 2014). The rate of degradation depends on a number of factors, such as temperature, moisture, ground surface condition etc. The decomposition process also releases harmful gases, such as CO_2, CH_4 and N_2O (Emery & Mosier, 2015), which directly impact the storage's ventilation and safety arrangement if it is enclosed. The maximum moisture content for corn stover bales has been suggested to be 20-22% (wb) for safe storage (Huang et al. 2012; Shah and Darr 2014).

Brechbill and Tyner (2008) found the dry matter loss of straw bales wrapped with twine, net and plastic over a 6-month period to be 18.8%, 8.4% and 6.15%, which correspond to $0.49/dt, $1.77/dt and $2.48/dt respectively. For corn stover bales with less than 25% moisture content, Shah and Darr (2014) reported 3% dry matter loss if the biomass is stored under roof and 5% dry matter loss if the biomass is tarp-covered. By comparison, Shinners et al. (2007) reported 17-38% dry matter loss for bales stored outdoor and 2-5% dry matter loss for bales stored indoor. Sultana et al. (2010) reported the cost associated with four methods of straw bale storage - on-field; outdoor on a crushed rock base; open structure under a roof and on a crushed rock base; and enclosed structure with a crushing rock base to be $0.9-1.8/dt, $2.0-2.7/dt, $5.4-7.2/dt and $9-13.5/dt, respectively.

The location of the storage site is also an important element of crop residue supply chain logistics. Previous studies have analyzed several inventory management strategies. The analysis by Tavener (2011) suggested keeping 2.5 days of usage as on-site storage and multiple off-site satellite storage each holding corn stover collected from approximately 160 acres. Yue et al. (2013) discussed several storage site location strategies under the multi-scale modeling and optimization framework. In addition, they also probed the potential of establishing independent pre-treatment depots with an aim to provide feedstocks to multiple biomass consumers in the region according to their demand of biomass quantity and quality.

After corn stover is baled and transported to a storage site, it will undergo moisture change and dry matter loss in the following months. The biomass feedstock's quality will be impacted by the microbiological reactions take place (Karunanithy et al., 2013). While these reactions can be influenced by a number of factors, such as ambient temperature, relative humidity, storage site ground cover, bale cover, air flow (wind velocity) (Montross & Crofcheck, 2004; Shah et al., 2011; Lynn et al., 2014), the generally recommended moisture content for long-term storage is below 17.5% db (Karunanithy et al., 2013) or below 0.9 water activity (Igathinathane et al., 2008) or below 20% wb (Athmanathan et al., 2015) to minimize dry matter loss. However, due to the diversity of crop residue materials (and other biomass), there is no universal model that can adequately predict crop residue's moisture change over time over a large range of temperature and relative humidity (Karunanithy et al., 2013).

2.3 Supply Chain Risk Analysis

2.3.1 Risk Analysis

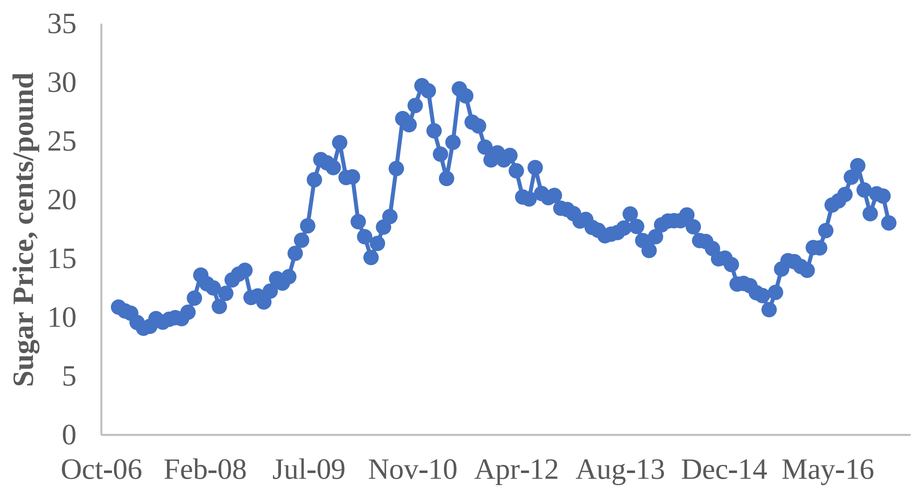
According to Takata and Yamanaka (2013), the importance of supply chain risk management was recognized in the late 1990s across many industries and further developed in later years. Risk is inevitable, because there are always elements that are uncertain or unknown to decision-makers (Vilko et al., 2014). Yet risk is also relative to an individual or a company's risk-taking capabilities (a higher risk-taking capability can enhance a decision-maker's confidence), attitude towards risk (risk-averse, risk-seeking and risk-neutral) and expected profits (an investment with higher risk demands a higher expected profit) (Alghalith, 2006; Chiu & Choi, 2016; Pries et al., 2016; Tsai & Luan, 2016). While the first two criteria are inherent to individuals and organizations, the expect profits and the corresponding risks can be analyzed to develop risk mitigation strategies that can either increase the profit with a given level of risk or to reduce the level of risk with a given expected profit (Zhou et al., 2016). Giarola et al. (2013) summarized that a business' success depends on investors' willingness to take financial risks, which arose from environmental consciousness and investment decisions. Based on experiences obtained from projects in the woodworking industry, Bartkute and Tolocka (2013) proposed that risk management is the ongoing process of setting objectives, identifying risks, assessing risks, treating risks, controlling risks and communication and monitoring.

There are generally two sources of supply chain risks – supply chain disruption risk (SCDR) and supply chain operational risk (SCOR). While SCDR disrupts the supply chain, SCOR often refers to some expected variations that are known to exist in the supply chain (Chiu & Choi, 2016). Studies on the biomass industry supply chain generally identifies uncertainties in the SCOR parameters, which aggregate and lead to variances in the biomass delivered cost from an expected cost (Chen et al., 2016). Published studies have investigated and developed risk mitigation strategies in many parameters related to SCOR. Takata and Yamanaka (2013) described four common approaches for enterprises to mitigate supply chain risks: 1) securing supplies from a single supplier with multiple production sites or from multiple suppliers; 2) be prepared for using replacement supplies; 3) redeployment of production sites; and 4) maintaining a sufficient level of inventory. Due to the unique nature of biomass supply chain, especially crop residue, not all of these risk mitigation approaches are feasible. From the approach of pricing strategies, Mark et al. (2009) compared several energy cane pricing strategies through simulation and concluded that the best pricing strategy was the combination of a fixed production cost and some variable rate based on realized yield. Golecha and Gan (2016a) applied game theory to analyze the supply variability of cellulosic biomass in the U.S. They found that the fixed price quantity-inflexible biomass supply contract leads to the lowest risk in the early stages of the cellulosic biofuel industry. From the approach of securing biomass suppliers, to address the high year-to-year variations in the supply of biomass, Golecha and Gan (2016b) compared the difference between maintaining the supply area based on average yield density and “derisked” yield density to conclude that the “derisked” supply market structure minimizes the volatility in payout and similar average payout.

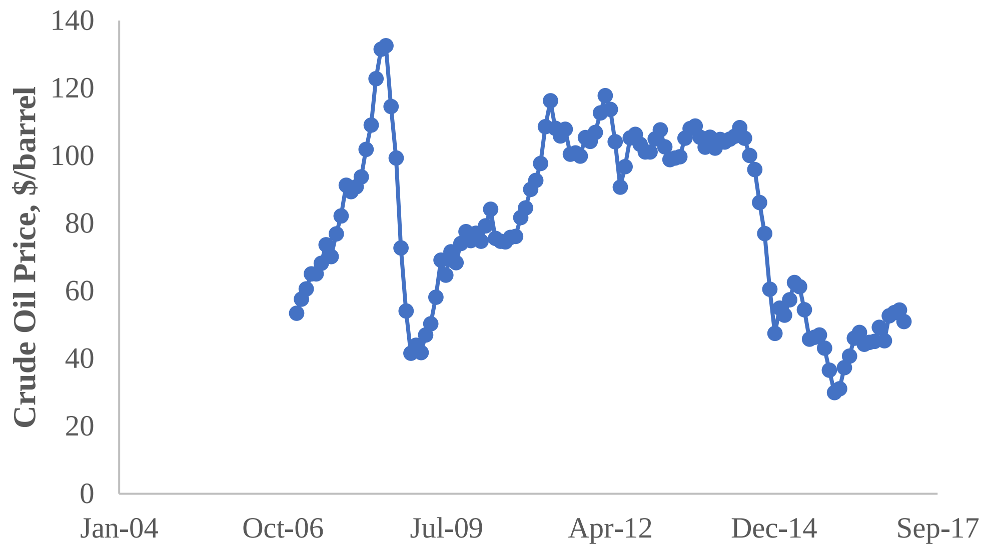
While there are a number of ways to measure risk, Goetschalckx et al. (2013) showed that for supply chain analysis, the standard deviation of a scenario’s profit or cost is appropriate to quantify supply chain’s risk to intuitively compare various supply chain network configurations (each presented as a scenario). Due to the stochastic nature of many of the variables involved and their complex relationship in a scenario, it is highly likely that multiple scenarios can achieve an expected delivered cost of biomass. However, the probability for each of these scenarios to be recognized in reality may be different. Therefore, Goeteschalckx et al. (2013) suggested to use risk curve (as illustrated in Figure A2) for robust supply chain design. It is in agreement with Giarola et al.’s (2013) approach of defining a multi-criteria decision hierarchy to balance the trade-offs between organizational capacities and competitive priorities and the trade-offs between cost efficiency, reliability and sustainability (Torjai et al., 2015).

2.3.2 Cluster Heat Map

On the supply side, despite the abundance of cellulosic biomass in regions such as North America (Sokhansanj et al., 2006; Hess et al., 2009; Li et al., 2012; U.S. Department of Energy, 2016), the biomass supply security over the lifetime of the biorefinery depends on the biomass producers’ willingness to participate in the supply chain (Altman & Sanders, 2012; Bergtold et al., 2014; Yue et al., 2014; Altman et al., 2015). However, the economic risks to a biomass project is not limited to the supply side, like all business, there are also economic risks associated with the variability in the product market prices. On the market side, the fluctuating price of final products and the competing commodities is among the primary parameters that impact the economic viability of a biorefinery project (Abbati de Assis et al., 2017). Figure 2.2 shows the market price of crude oil and sugar from January 2007 to March 2017. Despite the significant impact that the product market price can have on the financial performance of a biorefinery, it is often assumed to be constant throughout the lifetime of the biorefinery (Bergtold et al., 2014; Petter & Tyner, 2014; Arnold & Yildiz, 2015; Chiu et al., 2016; Pries et al., 2016; Tsai & Luan, 2016). While many studies consider variation in a number of supply chain parameters, the price volatility of final products has rarely been included in the risk assessment.



(a) Sugar historical price data (Average: 17.61 cent/pound, standard deviation: 5.13 cent/pound) (IndexMundi1, 2017). Bio-chemicals such as cellulosic sugar needs to compete in this market.



(b) Crude oil historical price data (Average: $80.50/barrel, standard deviation: $25.53/barrel) (IndexMundi2, 2017). Cellulosic ethanol needs to compete in this market.

Figure 2. 2. Market price of sugar and crude oil from January 2007 to March 2017

One approach to quantitatively visualize the combined the impacted of the supply and the market sides is through the cluster heat map. The cluster heat map (or simply heat map) is a data matrix of rectangles displaying compact data under three dimensions (rows, columns and colours) (Wilkinson & Friendly, 2009). Its application is well known in natural science and arguably the most widely used graph in biomedical science (Weinstein, 2008). Despite a heat map's application, the critical components of a heat map are dimensions shown in the data matrix display. Zhang et al. (2012) provided a general biclustering data structure as shown in Figure 2.3. In generally, the x and y dimensions are the independent variables, and the colour of the rectangles in the data matrix indicates the intensity of the dependant variable, which is often the variable of interests.

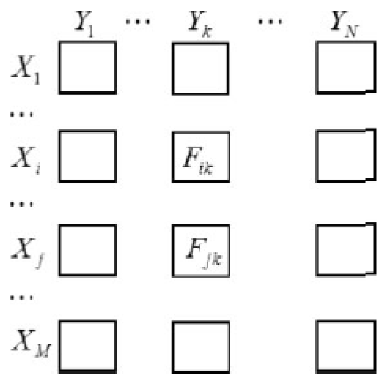


Figure 2. 3. Biclustering data structure (adopted from Zhang et al., 2012)

For the purpose of this thesis, the biomass supply cost distribution, the supply system operation cost distribution and the product's market price distribution can be used as x and y dimensions, and the values of the resulting expected annual ROI (the variable of interest) will be indicated by a scale of colours as shown in Figure 2.4. A ROI heat map does not impact the biconditional calculation of the final expected annual ROI, but it can effectively visualize the impact of operation costs and product market price on the economic outcome of the analyzed project. In other words, its main application is to facilitate the communication between all parties involved in the project. When ROI heat maps are produced for a base case scenario and a scenario after a risk mitigation strategy is applied, the comparison between heat maps can provide visualized in-depth understanding of the impacts of the applied risk mitigation strategy.

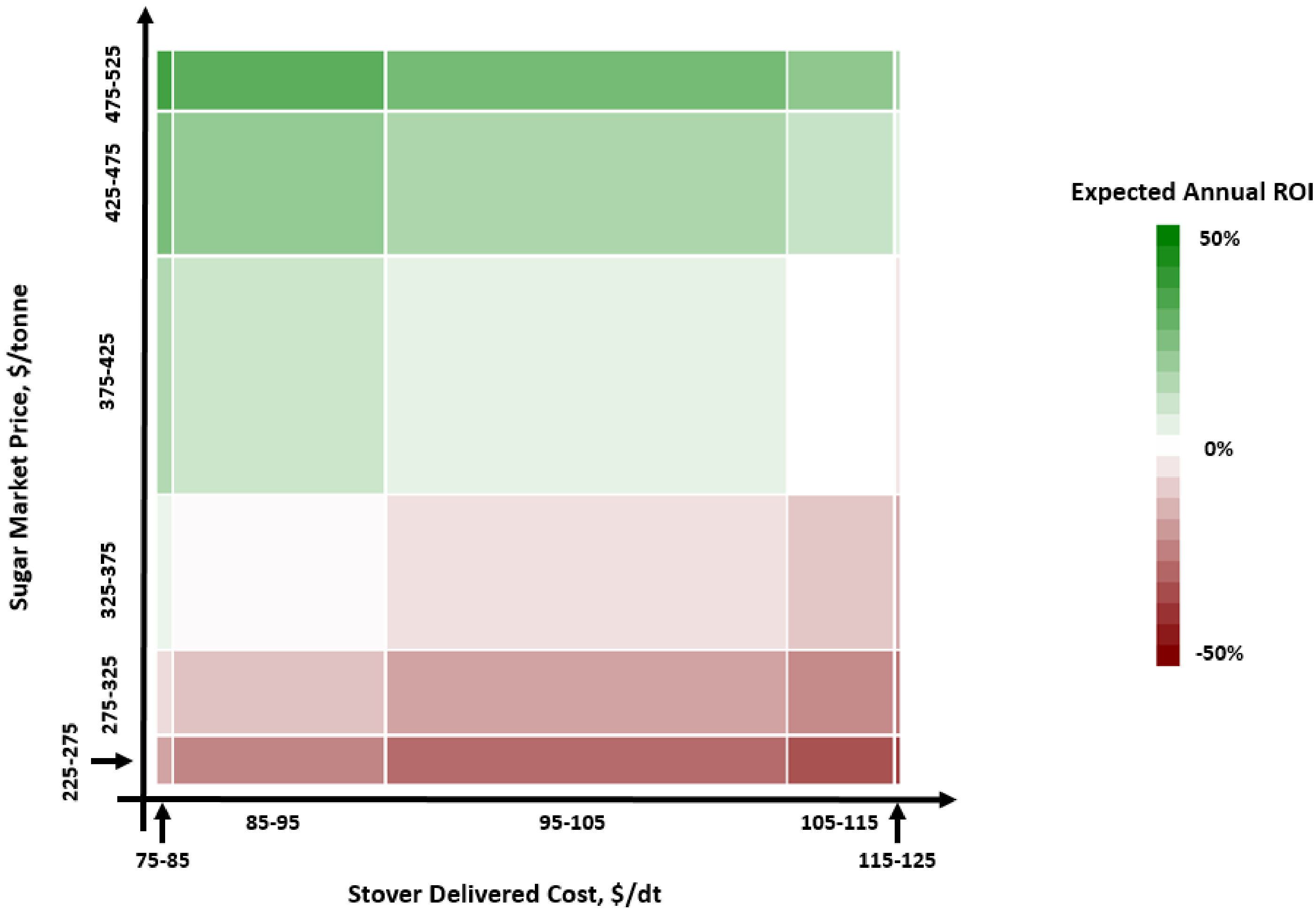


Figure 2. 4. Illustrative ROI heat map*

** Each rectangle represents a combination of sugar market price range and corn stover delivered cost range. The length of a rectangle indicates the probability of the occurrence of the respective corn stover delivered cost range. The width of a rectangle indicates the probability of the occurrence of the respective sugar market price range. Therefore, the area of the rectangle indicates the probability of the occurrence of the respective combination. Finally, the colour of a rectangle indicates the range of expected annual ROIs for the respective combination. A colour scale of the expected annual ROIs is provided on the side for reference.*

2.4 Supply Chain Governance Structure

2.4.1 Firm-Farm

Farm participation rate impacts the size of the supply area and the biomass delivered costs. The participation rate varies with environmental, social and economic conditions. Farm participation rate is a concern for existing and emerging biorefineries in short run as harvest, collection and supply of corn stover for industrial applications such as biofuel, bio-chemical and other bioproducts is a new practice for many corn growers. There are agronomic, environmental, contractual, logistics and market concerns coupled to the amount of crop residues removed from the field (Tyndall et al., 2011; Golecha & Gan, 2016[a]; Golecha & Gan, 2016[b]).

Bergtold et al. (2014) examined how contractual, market and harvesting arrangements could influence farmers' willingness to produce cellulosic biofuel feedstocks through data obtained from field surveys in Kansas. In addition to a number of identified influential contract attributes, they also concluded that farmers' willingness to participate varied by region and choice of feedstock. Altman and Sanders (2015) reported that Illinois and Missouri corn producers would potentially supply about 40% and 32% of their corn stover to bio-processors, while over 60% of the corn producers have balers, tractors and trucks needed to collect and transport stover. Qualls et al. (2012) conducted a survey in 12 southeastern U.S. states and showed that as the switchgrass price increases, producers' willingness to accept the bid price increases. However, the share of arable land converted to growing switchgrass is much less responsive. A survey conducted by Altman et al. (2015) in mid Missouri and southern Illinois showed 1.6%-2.4% increase in the participation rate per dollar in the price range of $10–20/dry ton.

Golecha and Gan (2016a) applied game theory to analyze the impact of the supply variability of corn stover in the U.S on its utilization rate and delivered cost. They found that on average, only 63% of collectable stover will be used for biofuel production. In another study, Golecha and Gan (2016b) developed an optimal contracting structure between biorefineries and biomass suppliers by finding the trade-off between different components of biomass cost including farm-gate cost, biomass transport, incentives to suppliers, nutrient replacement and financial impact (loss) to the biorefinery due to inadequate biomass availability. The impact of the biomass supply and farm participation rate on the performance of the biomass supply chain has also been investigated (Altman et al., 2015; Lauer et al., 2015; Galik et al., 2016; Wang et al., 2017).

2.4.2 Firm-Co-operative-Farm

Co-operatives have always played significant roles in the agriculture sector in developed and less developed regions (Altman, 2015; Borda-Rodriguez & Vicari, 2015; Grau, 2015; Terry and Ogg, 2017; Verhofstadt & Maertens, 2014; Wittman et al., 2017). In the traditional form, co-operatives pay close attention to co-operation among members, i.e. sharing labour, equipment, and other resources. The new generation of co-operatives, however, usually prioritize members' economic benefits by adopting corporate management based on stock. While co-operatives differ from each other in background, rationality, operations and guidelines, there are four common key principles critical to a co-operative's sustainability and success: 1) democratic control by members, 2) democratic control of capital, 3) autonomy and independence and 4) member education (Susilowati et al., 2014; Altman, 2015). Together, the four principles aim to ensure a leveled playfield for all members while independent farm owners still retain their economic independence and control over their own operation at an established standard.

Many studies analyzing the structure and benefits of co-operatives have been conducted in the agriculture sector. For instance, Verhofstadt and Maertens (2014) identified famers' co-operatives as the key vehicle in the growth of smallholder farm sector in Rwanda. From the cross-sectional survey data collected in 2012 (horticulture, coffee and maize), they observed that the household income of co-operative members is 60% higher than that of non-members. Furthermore, co-operative members in general sell a larger share of farm produce, spend more on inputs and use more modern technologies in their operation than non-members do. Tenzin and Natsuda (2016) analyzed the performance of Pam Dairy Primary Cooperative, which was formed by 22 founding members in 2005. They observed that the member households' annual earning is 55% higher than non-member households'. They concluded that the co-operative's success was partially due to the region's longstanding tradition of cooperation to maintain religious and social institutions. However, they have also observed a decline of strong bonding and mutual trust among families from different communities over the past few years. Terry and Ogg (2017) examined the support Swazi small sugar cane famers received from the Swazi state and the farmers' co-operative. They observed that in 2014, the average profitability for members of the farmers' co-operative was 14.3% higher than Swaziland's national average. While the most profitable farmers' co-operative's earning was four times the national average in 2014, the worst performing farmers' co-operative made a net loss due to weakness in operational factors.

2.5 Knowledge Gap and Research Objectives

Through the literature review, there exists a rich body of knowledge developed from studying the supply chain logistics and characteristics of various biomass. Facing the growing concerns over the risk arising from variability in biomass supply systems, there is an urgency for the biomass industry to recognize the importance of the concept of "biomass supply security" from three intertwined perspectives: quantity, quality and unit price (as shown in Figure 2.5).

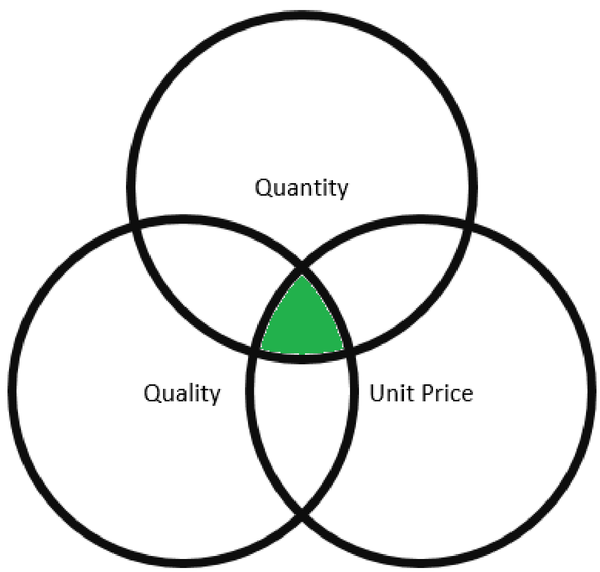


Figure 2. 5. Three pillars of biomass supply security*

**For an industrial project utilizing biomass to produce biofuel or bio-chemical, there must exist a stable and sufficient amount of biomass to support the biorefinery's annual operation through its lifetime, thus, the first perspective, quantity. At the same time, an industrial scale biorefinery demands a minimum quality from its feedstock in order to achieve the desirable yield and operation efficiency, thus, the second perspective, quality. When a biorefinery can receive a stable quantity of high quality feedstock, it guarantees the biorefinery can produce a targeted amount of commercial quality product for the market. However, most of the time, the produced* *biofuel and bio-chemical must compete with similar products produced through other means in the same global market. Therefore, depending on the expected price and its variance of the product, the biorefinery can only afford a maximum unit biomass delivered cost, thus, the third perspective, unit price. As indicated by the green area, the most preferred scenario is to have sufficient quantity of high quality biomass at a unit price that helps the biorefinery to achieve its economic goals over its lifetime.*

In addition to the uncertainties in biomass supply security, the economic wellbeing of a biomass project is also vulnerable to its product market price. From the literature review, a lack of discussion on quantifying the combined impact of variability in the supply chain system and volatility in the product market price on the overall economic performance of a biorefinery has been identified. As a result, this thesis focuses on industrial-scale feedstock supply risk analysis, and aims to quantify the economic benefits and risks of a biomass project experiencing fluctuations in biomass supply costs and bio-product market prices. The outcome of this study can facilitate and promote the discussion on operational standards, risk mitigation strategies, business structures and policies among biomass producers, investors, politicians, engineers, academics and financial institutions. Furthermore, the approach developed in this study can be generalized for biomass projects utilizing biomass other than corn stover.

Chapter 3. An Industrial Case Study

3.1 Synopsis

In February 2016, Comet Biorefining Inc. has announced that the proposed dextrose sugar plant located in the TransAlta Energy Park in Sarnia, Ontario would come online in 2018 to produce 60 million pounds dextrose sugar annually from local corn stover and probably wheat straw as well. In this chapter, the proposed supply area, economics and case study scenarios are examined. The quantified economic performance and risk analysis approach developed in this study is applied to this industrial case study for validation and illustration, which are discussed in Chapter 4, 5 and 6.

3.2 Supply Area

The large size of the agricultural sector in Canada leads to the production of abundant amounts of crop residues. Li et al. (2012) estimated that Canada produces on average 48 million dry tonnes of harvestable crop residues per year, which can be considered as feedstock for the production of biofuel and bio-chemicals. As the third largest crop residue producer, Ontario produces 10.78 million dry tonnes of harvestable crop residues (Saskatchewan and Alberta produces18.65 and 13.94 million dry tonnes of harvestable crop residues, respectively), which includes 62.6% of Canada's harvestable corn stover, approximately 7 million dry tonnes.

This study examines the ongoing development of a cellulosic sugar production facility located in Sarnia, Ontario as shown in Figure 3.1. The targeted corn stover supply area includes the nearby four counties, Huron, Middlesex, Lambton and Chatham-Kent. Sarnia is an ideal location for the project, because in addition to the abundant amount of corn stover available in Southwestern Ontario, it is also home of more than 60 refineries and chemical plants all within the 25 km radius of Sarnia's Chemical Valley (Environmental Justice Atlas, 2016). However, this location also introduces a challenge to the supply chain system – the facility is not at the center of the supply area. Lake Huron is located at the west side of the supply region. Thus, the required corn stover must be provided from the corn fields to the south, the east and the northeast of the facility in Sarnia. This geographic feature of the supply area can make the logistics system more challenging in comparison to regions such as Iowa in the United States where corn stover is usually available in continuous acres within a relatively circular-shaped supply area. This feature can lead to a large supply area with inefficient logistics operations, in particular transportation. It is expected that the increment of biomass supply is less than a circular supply area with increasing supply radius.

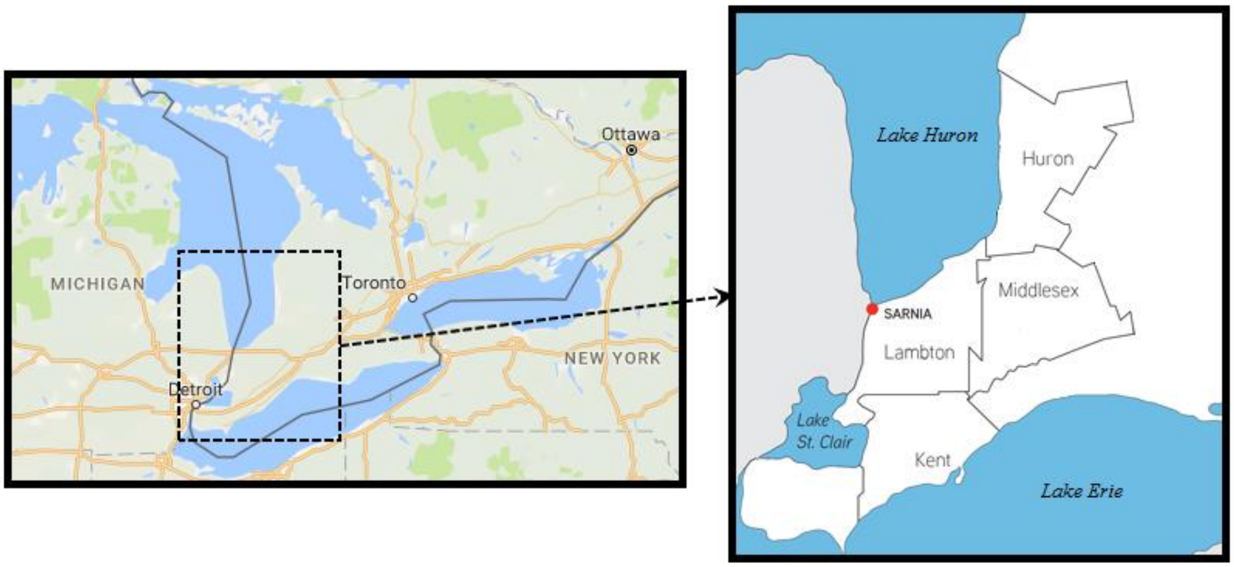


Figure 3.1. Map of Southwestern Ontario. Four major corn growing counties of Huron, Lambton, Middlesex and Kent are considered as the supply area for the proposed cellulosic sugar plant. The facility is located in Sarnia, Lambton (Google Map, 2015; Colliers Intern International, 2017)

Duffy and Marchand's (2013) study estimated 250,000 tonnes of stover can produce 115,000 tonnes of cellulosic sugar and 90,000 tonnes of lignin by-product. Marchant (2015) reported the total corn field sizes by average yield category in the supply area as shown in Table 3.1 and with an average grain yield of 158 bushels/acre from all corn fields, he estimated over 500,000 dry tonnes of stover are available in the targeted supply area for processing. Statistic data from Ontario's Ministry of Agriculture, Food and Rural Affairs (OMAFRA) show that there are considerable fluctuations in the amount of field growing grain corn from 2007 to 2013 as shown in Figure 3.2. Based on the average value, the amount of corn stover available increases significantly with increasing supply radius initially as illustrated in Figure 3.3. However, because the facility is not located in the center of the supply area and the supply area is limited to the four nearby counties, the amount of corn stover available reaches a near-maximum value when the supply radius reaches 180 km. Figure 3.4 shows the average amount of stover available for sustainable stover harvesting from each township in the supply area. Since some of the townships have less agricultural activity than others, a township's stover quantity does not scale linearly with its area.

Table 3. 1. Corn field acres by average yield category in the supply area

Year	2007	2008	2009	2010	2011	2012	2013
Corn Field Acres, thousand acres	689.8	489.0	545.1	547.0	542.2	688.7	559.7
150-159 bu/ac, thousand acres	67.2	33.6	80.0	50.3	42.4	37.1	45.2
160-169 bu/ac, thousand acres	54.2	52.7	69.6	61.7	79.1	66.2	69.2
170-179 bu/ac, thousand acres	29.5	50.5	61.9	88.1	90.7	66.5	80.0
180+ bu/ac, thousand acres	40.1	248.2	123.3	204.1	221.1	308.9	277.2

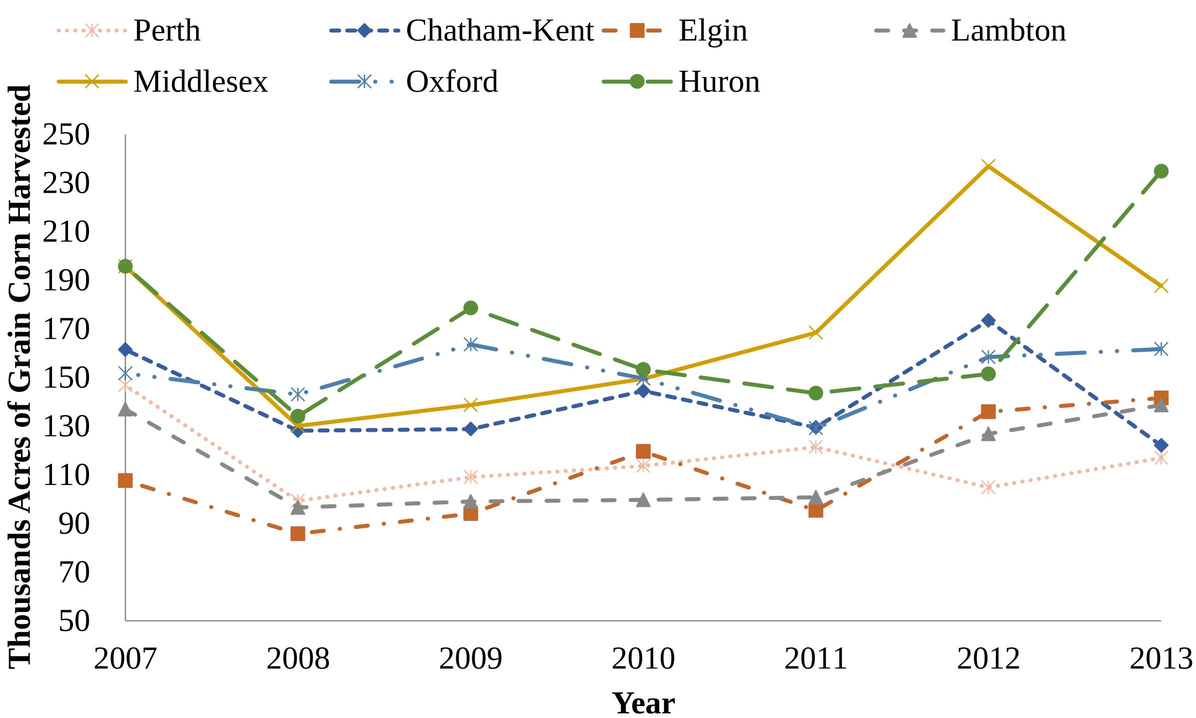


Figure 3. 2. Grain corn production from 2007 to 2013

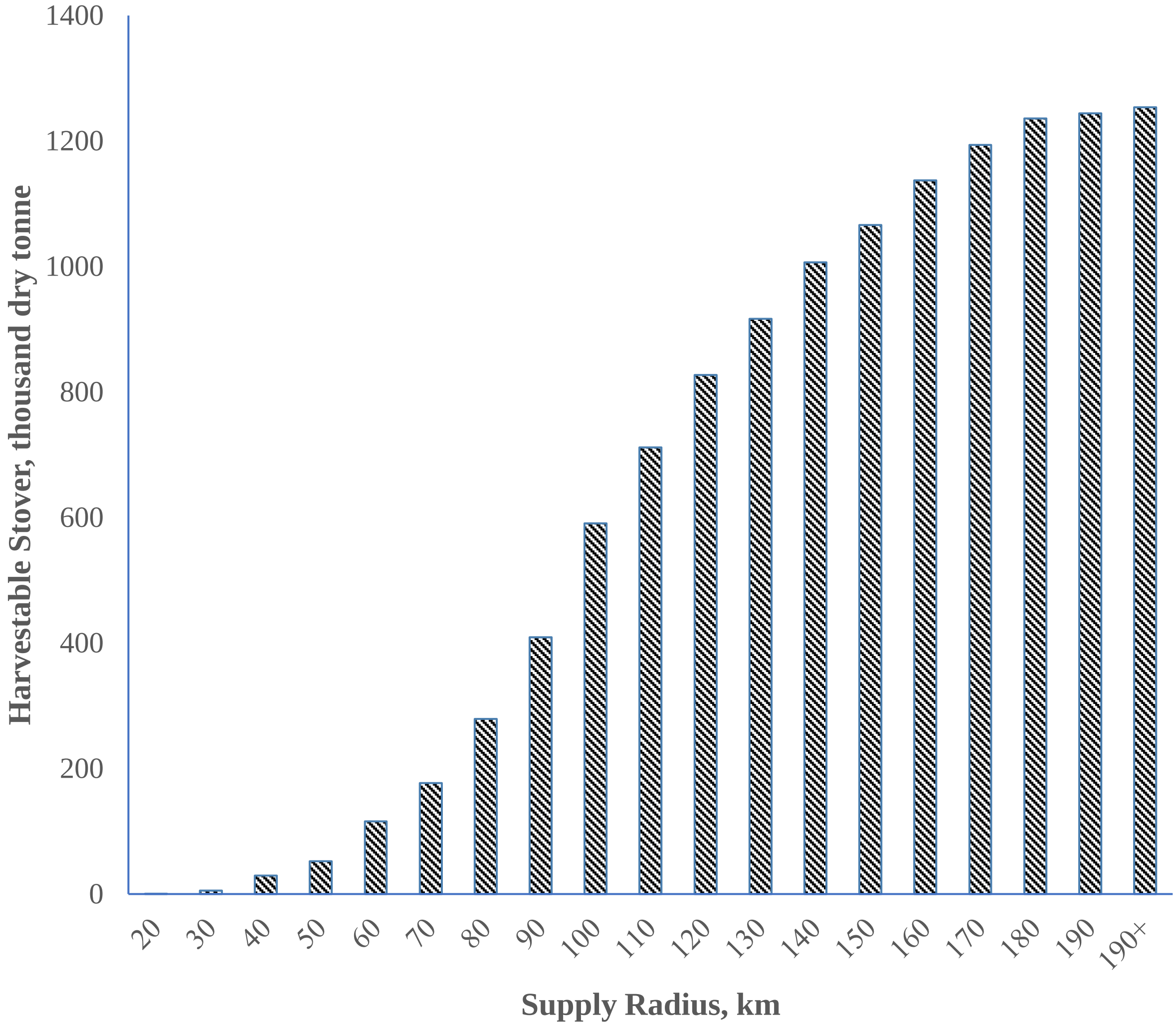


Figure 3. 3. Regional corn stover supply curve*

**This figure indicates the amount of corn stover available in the supply area as the maximum transportation distance to the biorefinery increases. For instance, at 20 km supply radius, there is barely any corn stover available, but at 120 km supply radius, there are over 800,000 dt of corn stover available for harvesting. As the supply radius approaches the outmost boundary of the supply area (170-190 km), the amount of harvestable corn stover approaches its maximum value (~1,300 dt)*

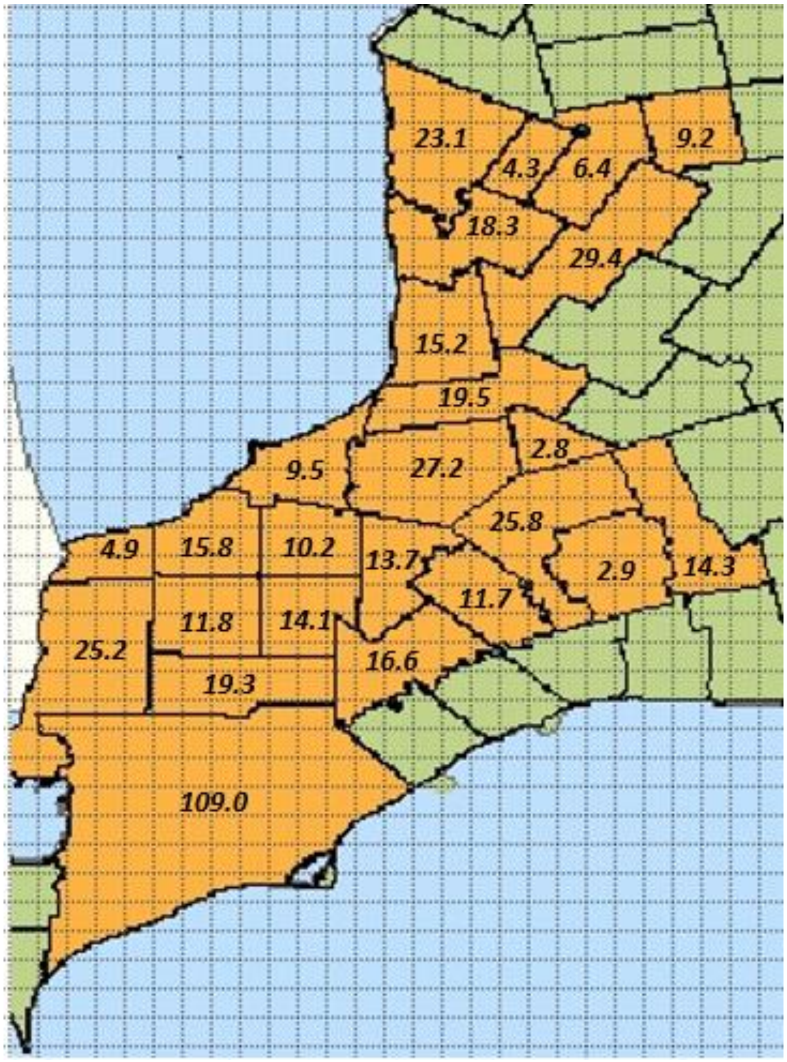


Figure 3. 4. Township average stover availability (thousand dry tonnes)*

**Each orange polygon indicates a county in the supply area. This figure demonstrates the estimated amount of harvestable corn stover available in each county. Since some counties have more agricultural activity than others, the amount of harvestable corn stover available in each county does not necessarily scale with a county's land area.*

The typical corn growing season in the region under study is from early May to mid-October. To avoid unfavorable weather conditions in winter, corn stover is usually harvested right after corn harvest till mid-January (personal communication with Cellulosic Sugar Producers Cooperative (CSPC) Inc. and Bioindustrial Innovation Canada (BIC) Inc., May 12, 2016). The harvested bales are temporarily stored at the roadside of corn fields and then transported either to the intermediate storage site or to the cellulosic sugar plant before mid-February. Thus, the corn stover harvest and transportation routines set maximum 90 days available for harvesting and 120 days for transportation. However, the number of working days is a function of weather conditions, the slope of soil surface, soil type, drainage characteristics, type of field operations and traction and flotation devices (American Society of Agricultural Engineers, 2000). Due to the lack of the soil data for the individual fields in the supply area, the number of working days in the harvest season is solely estimated based on the local weather data, particularly rainfall. Figure A3 shows the amount of rainfall and the number of working days in the supply area in the period of 2006-2015 (personal communication with Bioindustrial Innovation Canada (BIC) Inc. and Weather Innovations Consulting LP, January 15, 2016). It is assumed that the field operations are delayed by one hour for every mm of rainfall (Ebadian et al., 2011; Ebadian, 2013; Sokhansanj et al., 2006[b]), thus, the number of working days in a week is estimated to be in the range of 3 to 7 days.

3.3 Sugar Production Process

The conversion from lignocellulosic biomass to fermentable sugars can be complicated due to recalcitrance caused by the association of cellulose, hemicelluloses and lignin in the biomass. As a result, the conversion process generally requires pretreatment to open or partially break up the recalcitrant structure – cellulose chains embedded in hemicellulose matrix wrapped by lignin (De Vries & Visser, 2001; Jorgensen et al., 2017). A number of different pretreatment methods, such as steam explosion, biological treatment, steam treatment with sulfuric acid or sulfur dioxide and subcritical and supercritical water treatment, have been reported. Among these pretreatment methods, biological pretreatments tend to be less expensive but slower; physical and thermomechanical pretreatments require a substantial amount of energy and chemical treatments requires corrosion-resistant equipment, extensive washing and proper chemical waste disposal (Taniguchi et al., 2005). After pretreatment, hydrolysis of the exposed cellulose (also known as saccharification) can be done with acids or enzymes. In comparison, while enzymes are more expensive than acids are, they are selective, which leads to a relatively high yield, and require a lower temperature (Hellqvist, 1996). To date, dilute acid pretreatment combined with enzymatic hydrolysis has been considered to provide maximal sugar productivity and minimal loss of sugar (Hsu et al., 2010).

Through literature review, a rich body of studies on evaluating or optimizing the performance of specific pretreatment and hydrolysis process of biomass has been encountered. For example, Taniguchi et al. (2005) evaluated the effects of biological pretreatment of rice straw using white-rot fungi on the basis of quantitative and structural changes and susceptibility to enzymatic hydrolysis. They observed a net sugar yield (based on the amounts of cellulose of untreated rice straw) of 32% for glucose from rice straw pretreated with *P. ostreatus*. Hsu et al. (2010) reported that a maximal sugar yield of 83% was achieved when the rice straw was pretreated with 1% (w/w) sulfuric acid with a reaction time of 1–5 min at 160 °C or 180 °C, followed by enzymatic hydrolysis. Zhang et al. (2015) investigated the impacts of ionic liquid and alkaline pretreatments on the enzymatic hydrolysis of corn stover. They observed that the enhanced enzymatic digestibility of corn stover was mainly influenced by cellulose crystallinity. The proposed process for the production of high purity dextrose from corn stover and wheat straw is a proprietary, two-stage process that also produces hemicellulose extract and lignin as by-products (Comet Biorefining, 2018). However, the details on the pretreatment and hydrolysis other than the overall dextrose and lignin yield have not been released.

Despite the lack of released information on the pretreatment and hydrolysis process selected by the investing parties in the case study, it is possible to construct a simplified generic model of the two-stage process using bioprocess simulators, such as Aspen Plus, which was described by Alnur Auli et al. (2013) to contain, a rich databank of parameters and constants, a vast number of thermodynamic models and a library of standard unit operation blocks. Furthermore, Aspen Plus also has the capability for users to define new compounds and unit operations in conjunction with its build-in kinetic and thermodynamic models (Bafrani, 2010; Alnur Auli et al., 2013). Julian and Cardona (2011) also reported that Aspen Plus could be used to design and simulate lignocellulosic biomass pretreatment and hydrolysis while considering relevant kinetic models of chemical and biological reactions. However, the best use of Aspen Plus requires a fair amount of understanding of the chemical and biological reaction and thermodynamic kinetics of the process. This is usually obtained through analyzing experimental or industrial data from similar or the same processes (Granjo et al., 2015). Quintero and Cardona (2011) illustrated that if the material compositions and kinetic models of individual stages of the process have been well defined, Aspen Plus can be an effective tool to design and simulate the whole process at different scales. Within the scope of this study, there is a lack of information to construct a reliable simulation that best represents the production process in the case study and to validate the simulated results. In a future study, the simulation can be done with the support and validation of experimental data or released data from the current pilot scale operation in Sarnia and Italy from Comet Biorefining.

3.4 Proposed Investment

The economic characteristics of the biorefinery are specified based on the financial model developed by Duffy and Marchand (2013) and Marchand (2015) (Table 3.2). The target annual ROI of 15% over 10 years is considered for this biorefinery project in the base case scenario. The target ROI is the maximum expected ROI. The target ROI would be achievable if the average delivered cost of corn stover is $81.33/dt and the average market price of the cellulosic sugar is assumed to be $400/tonne. Lignin is considered to be the co-product of the conversion process. The conversion yields of cellulosic sugar and lignin are estimated to be 0.46 tonne and 0.36 tonne per dry tonne of corn stover, respectively. A ramp-up period of 18-24 months are considered before the facility reaches a steady state. During this time, the plant operations would be tested and debugged before full operation begins in the third year (Marchand, 2015). More details of the ramp-up period are provided in Table 3.3.

The purpose of applying the developed economic performance and risk analysis approach to this industrial case study is to validate the developed approach and to illustrate how the findings can facilitate the discussion of economically sustainable business structures and risk mitigation strategies among parties involved in the biomass project. As a result, variations in two major economic parameters, the cellulosic sugar price and feedstock cost, are considered while other parameters remain constant. However, it is possible to apply the developed approach to consider variations in multiple parameters.

Table 3. 2. Economic parameters for the cellulosic sugar production project in Sarnia, Ontario.

Capital Investment	
Plant Capacity (tonne/year)-Corn stover	63,000
Unit Capacity cost ($/(tonne/year))	280
Capital Cost ($)	17,640,000
Loan to equity ratio	1:1
Loan ($)	8,820,000
Equity ($)	8,820,000
Interest rate	5%
Loan payment period (year)	10
Price of cellulosic sugar ($/tonne)	400
Price of lignin ($/tonne)	40
Corn stover delivered cost ($/dt)	81.33
Sugar production cost ($/tonne)	40
Production and Revenue	
Cellulosic sugar production (tonne/year)	28,980
Lignin production (tonne/year)	22,680
Cellulosic sugar revenue ($/year)	11,592,000
Lignin production ($/year)	907,000
Total Revenue ($/year)	12,499,200
Operation costs	
Feedstock cost ($/year)	5,123,790
Sugar production cost ($/year)	2,520,000
Financing cost	
Loan payment including interest	1,142,230
Net Income-before tax	3,713,179
Net Income-after tax	2,970,543

**All monetary values are in Canadian dollars. The capital cost does not include the investment required to establish a dedicated harvesting and transportation fleet % (Duffy & Marchand, 2013; Marchand, 2015).*

Table 3. 3. The proposed 10-year cash flow estimation

Year	CAPEX ($)	Revenue ($)	Operating Cost ($) (feedstock+ sugar production)	Loan Payment ($)	Gross Gain ($)
0	-8,820,000				-8,820,000
1*		0	$2,160,947	1,142,230	-3,303,177
2*		$6,249,600	$5,982,842	1,142,230	-875,472
3		$12,499,200	$7,893,790	1,142,230	3,463,180
4		$12,499,200	$7,643,790	1,142,230	3,713,180
5		$12,499,200	$7,643,790	1,142,230	3,713,180
6		$12,499,200	$7,643,790	1,142,230	3,713,180
7		$12,499,200	$7,643,790	1,142,230	3,713,180
8		$12,499,200	$7,643,790	1,142,230	3,713,180
9		$12,499,200	$7,643,790	1,142,230	3,713,180
10		$12,499,200	$7,643,790	11,142,230	3,713,180
Annual ROI	15%				

**A ramp-up period of 18-24 months are considered before the facility reaches a steady state. During this time, the plant operations would be tested and debugged before full operations begin in year 3. It is assumed that in year 1, the facility incurs 50% of fixed costs, 25% of variable costs and no revenue. In year 2, 100% of fixed costs and 75% of variable costs are spent and 50% of revenue is generated. The administration costs were held constant at $250,000 per year to cover the cost of communicating with producers, sourcing biomass, logistics, etc. It is still assumed that the ROI calculation is over ten years even though full revenue potential is not reached until Year 3. The ROI is based on the return on private funds with a tax rate of 20% (Duffy & Marchand, 2013; Marchand, 2015), which is the result of applying tax incentive programs in Ontario, such as Scientific Research and Experimental Development (SR&ED) Program, that encourages Canadian businesses to conduct research and development in Canada.*

3.5 Communication with Industrial Partners

In order to assure the developed approach and its findings are relevant to the industry's needs, close communication was established with industrial partners (AGCO, Bioindustrial Innovation Canada (BIC) and the Cellulosic Sugar Producers Co-operative (CSPC)). AGCO is a global leader in the design, manufacture and distribution of agricultural equipment (AGCO, 2018). Through this study, valuable agricultural equipment performance data was obtained from AGCO for simulation. BIC is a not-for-profit organization based in Sarnia, Ontario focusing on providing critical strategic investment, advice and services to business developers of clean, green and sustainable technologies (BIC, 2018). Through communication with BIC, two proposed sugar production facility sizes were proposed, 310,000 dt/year (or 860 dt/day) and 63,000 dt/year (or 175 dt/day), which were presented as the more suitable capacities to the technology applied at the biorefinery. A hypothetical facility size of 187,200 dt/year (or 520 dt/day) was added later on to examine whether the complexity of the supply chain system scaled linearly with the biorefinery size. The CSPC is an Ontario based farmer's co-operative. The co-operative aims to support farmers to generate higher profits per acre of corn fields by establishing a corn stover market for cellulosic sugar production (CSPC, 2018). The CSPC suggested a likely scenario for the co-operative's involvement, which requires the co-operative to contract 46,000 acres of corn field within 90 km distance to the biorefinery. The biorefinery pays $30/dt for its annual biomass demand of 63,000 dt, and a portion (based on the percentage of ownership of the biorefinery) of the net profit from selling the produced sugar to the co-operative. The farmers' co-operative also collects a one-time membership fee ($500 plus $200/acre) from participating corn field owners.

Chapter 4. Impact of the Biorefinery Size on the Logistics of Corn Stover Supply

4.1 Synopsis

There exists a general trend in engineering economics to suggest that production facilities receive economic benefits from increased production capacities, but in the biomass industry, this observation has been challenged due to the increment in supply system logistics cost. In addition, as the production facility's capacity increases, the required initial capital for establishing a stable supply chain also increases. Many studies have estimated and optimized the biomass delivered cost for a given biorefinery size, and some investigated the economic challenges in the supply system for a biorefinery to achieve commercial-scale. In this chapter, the logistics factors that can impact the economic viability of a biorefinery are examined. Furthermore, the size of the required logistical resources, their associated capital costs and administrative and managerial supports are also estimated to demonstrate the level of complexity to develop the required logistical resources.

4.2 Objectives and Contributions

The commonly observed development of an economically promising biorefinery can be summarized into three phases - pilot scale, demonstration scale and commercial scale (Schwab et al., 2016). One of the primary challenges to reach the commercial-scale phase is to prove the biomass logistics system is able to meet the biomass demand of the biorefinery in a cost-efficient manner throughout the lifetime of the bio-conversion facility (Schwab et al., 2016). A bio-processing facility often benefits from the increased capacity quantified by the scale factor or the economy of scale. In the emerging biomass industry, however, a number of previous studies have illustrated such benefits can be hindered as the biomass delivered cost could significantly go up with the increase in the size of the facility (Nguyen & Prince, 1996; Arbogast, 2012; Duffy & Marchand, 2013).

Through literature review, a rich body of knowledge has been developed on estimating the biomass delivered cost for a given biorefinery size. However, in addition to the delivered cost, the size of the required logistical resources, their upfront capital costs and their availability in rural areas, especially during the short harvest season, can impact the economic viability of a biorefinery. These logistical resources include (1) harvest area and contracted fields (2) logistics equipment fleet and the workforce to run this fleet, and (3) intermediate storage sites and their inventory levels. These resources are essential to mobilize a large quantity of biomass from fields to the gate of a biorefinery. The characteristics of the supply area such as the distribution and size of fields, biomass yield, farm participation rate and other local conditions such as weather and harvest window impact the size of the required logistical resources to meet the biomass demand of the biorefinery.

In this chapter, the required logistical resources for three biorefinery sizes (i.e. small, medium and large scales) are quantified. The logistical resources are then compared between these scenarios in order to measure the impact of the biorefinery size on the required logistical resources. Local conditions and the dynamic and stochastic nature of the biomass logistics system are considered in the comparison. In addition, the biomass delivered cost distribution is estimated for each biorefinery size and is used to quantify the probability of meeting a target biomass delivered cost.

This chapter aims to enhance the understanding of the logistics factors that can impact the economic viability of a biorefinery based on local conditions such as the distribution of biomass producers, biomass yield and harvest window. This chapter also determines the level of complexity to develop these logistical resources. The size of the required logistical resources, their associated capital costs and administrative and managerial supports are used as the basis to compare the complexity of the biomass logistics systems for the considered biorefinery scenarios. Another contribution of this chapter is the modeling and evaluation of the non-circular supply area for the considered case study that consists of thousands of relatively small farms.

4.3 Methodology

4.3.1 Data Base Structure for Geographical Information

When handling the geographical information of a specific region, a geographic information system (GIS) is often designed to capture, store and present the relevant geographic data. While pixel units are the dominant unit of a GIS, there is an increasing interest in using polygonal units. Xu and Brown (2016) identified a clear trade-off between using pixel and polygonal units –

using polygon units can better present realistic spatial patterns, but using pixel units can provide more accurate location information. Furthermore, Fisher (1997) suggested three major reasons for using rectangular pixel units in GIS:

1. A geographical plane can be fully covered by pixel units.
2. Rectangular grid systems have been used for many years and are consistent with the National Grid and longitude and latitude.
3. The original geographical information is likely to be first captured through pixel-based data.

As shown in Figure 4.1, when pixel units are used in GIS to represent the real world, there will be some degree of disorientation, especially to objects with irregular shapes, and the issue may be more significant if the GIS is three-dimensional. For the scope and application of this study, location of the biorefinery, intermediate storage and participating farms, stover yield and corn field size of each participating farm and the general shape of each county are the most important information in the GIS, thus, a pixel-unit based GIS should be sufficient.

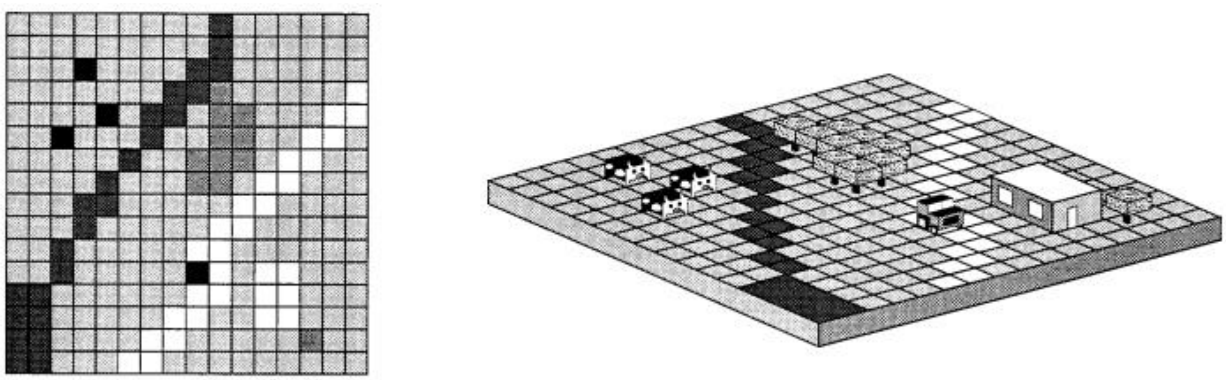


Figure 4. 1. Pixel view of the world (adopted from Fisher, 1997)

Based on the 2011 agricultural census of Statistics Canada data on the individual farms for each township in the supply area, the supply area is divided into 6.6×6.6 km^2 square grids as shown in Figure 4.2. The size of the grids was chosen to capture each township's shape and to reflect the number and size of farms in each township. Each grid contains supplier information including the number of corn fields, field size, field's grain and stover yield and its coordinate within the supply area. Figure 4.2 illustrates how the grids capture the region's geographical information and one aspect of the supplier information (acres of corn fields with grain yield of 180 bu/ac).

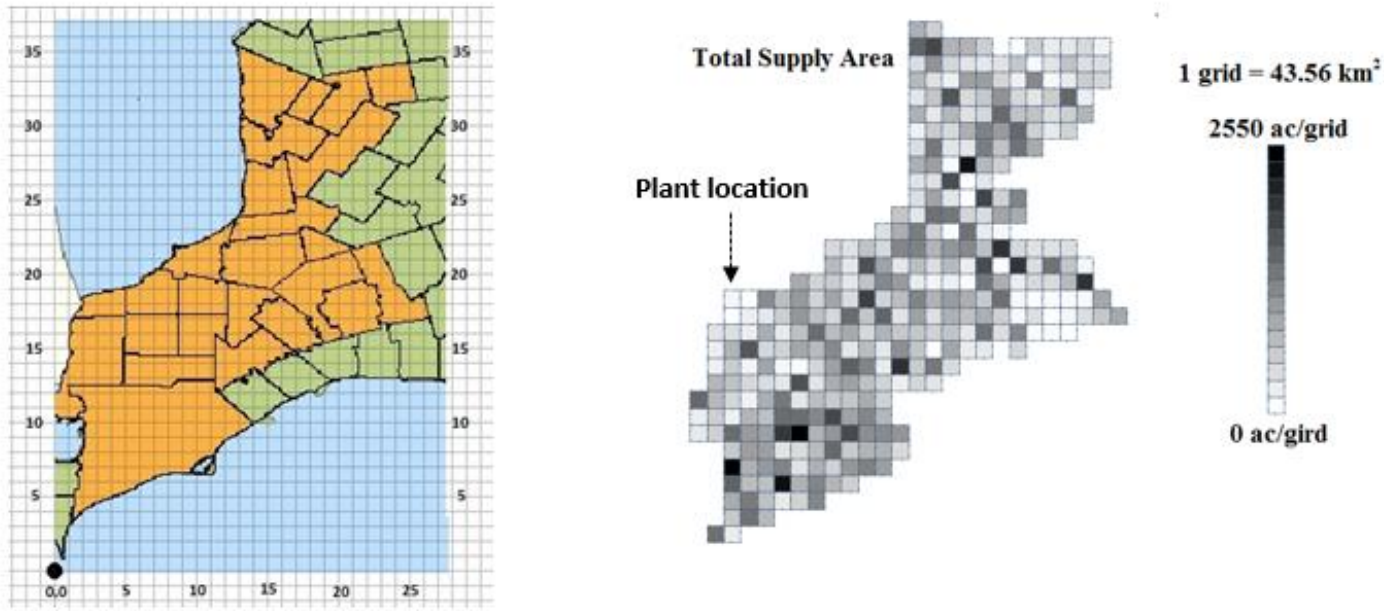


Figure 4. 2. Polygon grids of townships in the supply area

4.3.2 Monte Carlo Simulation

Monte Carlo simulation procedures (or experiments) are being used more and more often to deal with stochastic systems, which may still be described in a mathematical structure of sufficient details (Mode & Gallop, 2008). As an alternative approach, Monte Carlo simulation relies on intensive use of computers to repeat random sampling in a defined domain to obtain numerical results (or a distribution of numerical values) of the variable of interest. At the same time, when Monte Carlo simulation is used, two guiding principles should be followed in order to make the procedures and results of Monte Carlo simulation transparent (Mode & Gallop, 2008):

1. The underlying mathematical structure of a Monte Carlo simulation model should be provided in sufficient details so that the results can be duplicated to some extent.
2. The software used in the Monte Carlo simulation should be reported for scientific openness, even though the software may not be freely open to the public.

Due to the complexity and uncertainties involved in the biomass supply system, no decision-maker can have all necessary knowledge over the entire supply chain, thus, the management's main concern is the robustness of the supply chain instead of optimality (Ingalls, 1998; Deleris & Erhun, 2005). To achieve the desired robustness, Monte Carlo uncertainty assessment (or Monte Carlo simulation) is adapted to find a reliable expected profit and its variance. For example, Izquierdo et al. (2010) developed a log-normal distribution supply-cost curve for biomass energy resources in the Canary and Balearic Islands in Spain. The distribution function thus obtained is used to estimate the economic potential and feasibility of utilizing biomass energy in the region. Marvin et al. (2012) applied mixed integer linear programming to optimize the location and biomass demand capacity of bio-ethanol production facilities in a nine-state region in the Midwestern US. They considered variations in the supply chain parameters and the goal is to maximize the overall net present value. Arnold and Yildiz (2015) utilized Monte Carlo simulation to evaluate the probability density function of the net present value of decentralized renewable energy infrastructures. The function is used as the basis for evaluating an investment's risk and risk-to-return ratio. Golecha and Gan (2016) developed a risk mitigation strategy based on derisked usable stover supply to help biorefineries cope with the high year-to-year corn stover supply variations (20-30%) in major US production regions.

4.3.3 IBSAL-MC

Due to the capability and flexibility of simulation in modeling and evaluating complex dynamic systems, it has been widely used to estimate the logistics costs while incorporating the dynamics and stochastic nature of biomass logistics systems. Sokhansanj et al. (2006[a], 2006[b]), Kumar and Sokhansanj (2007), Hess et al. (2009), Nilsson et al. (2010), Stephen et al (2010), Zhang et al. (2012) and Ebadian et al. (2014) are examples of the studies that developed simulation models to evaluate biomass logistics operations. Furthermore, simulation modeling has been used to determine the potential location of satellite storage sites in the supply area (Cundiff et al., 2009). Another application of simulation modeling was to find the most and least favorable locations and sizes of bioenergy plants based on the performance criteria including the delivered feedstock cost, energy consumption, and CO_2-eq emissions (Zhang et al., 2012). Although simulation modeling is a powerful tool for a detailed evaluation of biomass logistics systems under different circumstances, the results are not necessarily the optimal solutions among the alternatives.

In this study, the Integrated Biomass Supply Analysis and Logistics Multi-Crop model (IBSAL-MC) is used to perform the Monte Carlo simulation. The parameters and governing equations in the simulation are discussed in greater details in Appendix B. In this section, the simulation structure, input data and output data of IBSAL-MC are discussed. In IBSAL-MC, the entire logistics system operates to meet a facility's fixed daily biomass dry matter demand. The advantage of applying IBSAL-MC for this study is that it allows users to introduce new mathematical models or modify the existing mathematical models to meet a project's specific situation and objectives. In order to meet this demand, the simulation runs on an hourly basis to provide the most realistic understanding of how the logistic machines operate and where the logistic machines locate at different times.

Figure 4.3 shows the simulation used in this study to quantify the impact of the biorefinery size on the logistical resources required to mobilize agricultural biomass from fields to the gate of a biorefinery. The methodology is developed for using corn stover as the feedstock to produce biofuel/bio-chemical. However, the developed methodology can be applied to other types of crop residues. It is comprised of three components:

Input Data: As shown in Figure 4.3, the input dataset includes all the data associated with the biorefinery, corn fields, logistics equipment and storage sites. Some of the input parameters are considered as variables to reflect the temporal and the spatial variations in the supply system. These parameters include biomass yield, harvest window, harvest moisture content, bale bulk density, farm participation rate, dry matter loss, equipment capacity and efficiency, machine breakdown and repair times, winding factor and road transportation time (Table A6 and A7).

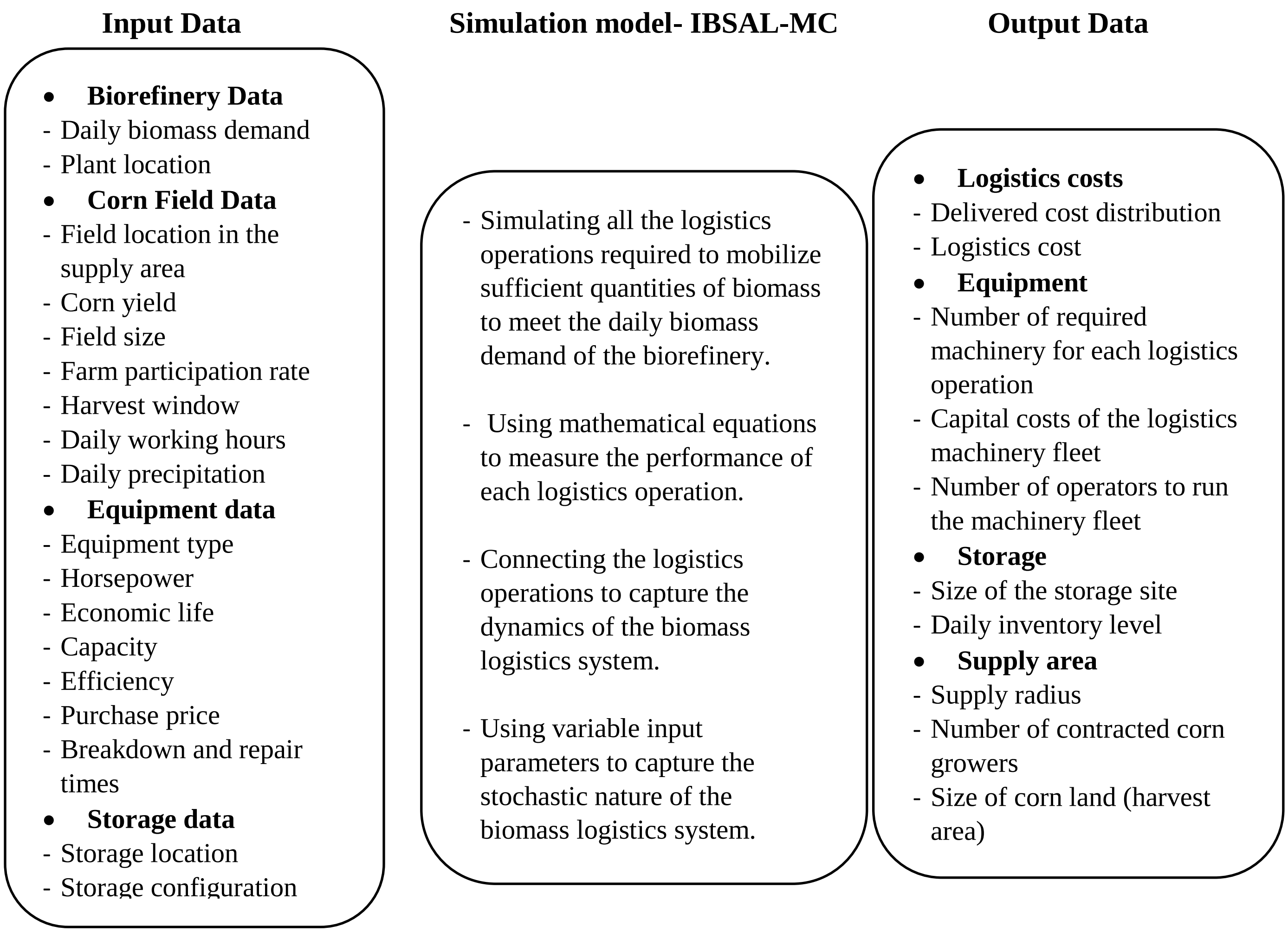


Figure 4. 3. The developed methodology to quantify the impact of the biorefinery size on the logistics of corn stover supply

Simulation model: IBSAL-MC is applied to quantify the required logistical resources for a given biorefinery size. IBSAL-MC is a modified and improved version of the simulation model, IBSAL (Sokhansanj et al., 2006b). It is a push/pull simulation model in which the entire logistics system is planned and scheduled based on the daily biomass demand of the bio-conversion facility (pull scheduling) and the harvest schedule (push scheduling). The push part simulates field operations based on the corn harvest window and the local weather conditions. Corn stover must be harvested and removed from fields in a short period of time, because corn growers tend to prepare the fields for the next cropping season after the grain harvest season and the fields are not usually accessible in winter and early spring (Hess et al., 2009). Thus, intermediate storage sites are essential to meet the annual demand of the facility in the post-harvest season. The rest of the supply system acts as a pull system in which corn stover is pulled either directly from fields (i.e. just-in-time) or intermediate storage sites based on the daily biomass demand of the facility. Therefore, the push part of the logistics system must harvest and collect sufficient amounts of biomass to meet the annual biomass demand considering the potential dry matter loss in the logistics system. The pull part only handles and transports the amount of biomass required to fulfill the daily biomass demand of the facility throughout the year. This structure of the agricultural biomass logistics system dictates the size of the logistical resources required to meet the biomass demand of a biorefinery.

In this study, IBSAL-MC is modified based on local conditions, agricultural practices and other characteristics of the case study. It is also modified to meet the objectives of this study. The dynamics and stochastic nature of the agricultural biomass logistics system is modeled in IBSAL-MC and reflected in the final results. Due to the variability in the input data, IBSAL-MC is run for multiple replications. Each replication shows the performance of the logistics system under a specific set of input data.

Figure 4.4 shows a simple schematic of the agricultural biomass logistics system in IBSAL-MC. The simulated logistics system is divided into three time periods:

(1) Harvest season/Field operations: The harvest season covers the period of time during which corn stover is harvested, collected and transported to the roadside of corn fields. Thus, this period covers the following field operations: shredding and windrowing, baling, bale collection and stacking at the roadside of corn fields. Since grain corn is the primary product, stover harvest season is scheduled after the grain harvest (Martinez-Kawas, 2013). Weather conditions, especially precipitation, have a significant impact on the suitability of soil to run field operations and the length of the harvest season (Hess et al., 2009).

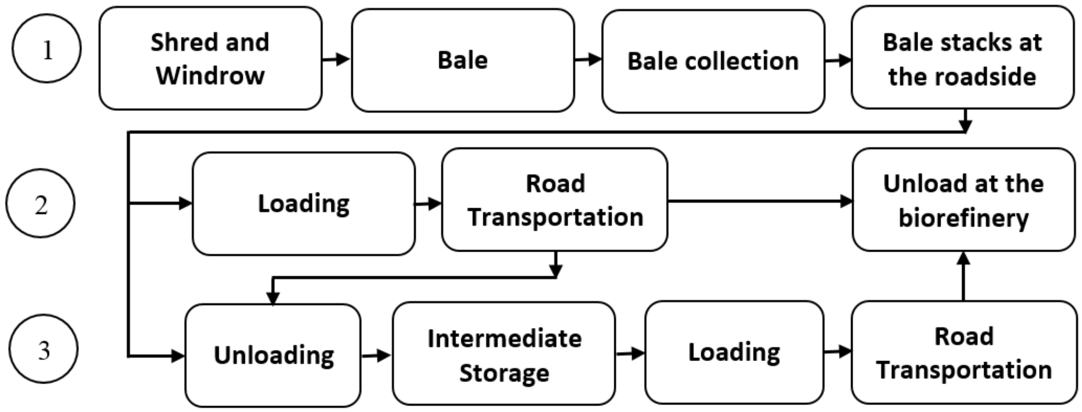
(2) Roadside bale removal and transportation season/Just in time delivery: This period covers the time gap between the start of the harvest season and the corn planting season. Within this period, the stored bales at the roadside of corn fields are removed from the fields and transported either directly to the bio-conversion facility or to the intermediate storage sites. All the stored bales at the roadside of the fields must be removed before the commencement of the next cropping season. The logistics operations during this period include loading, transportation and unloading operations. The length of this period depends

on the weather conditions and the supply agreement between the facility and the corn growers.

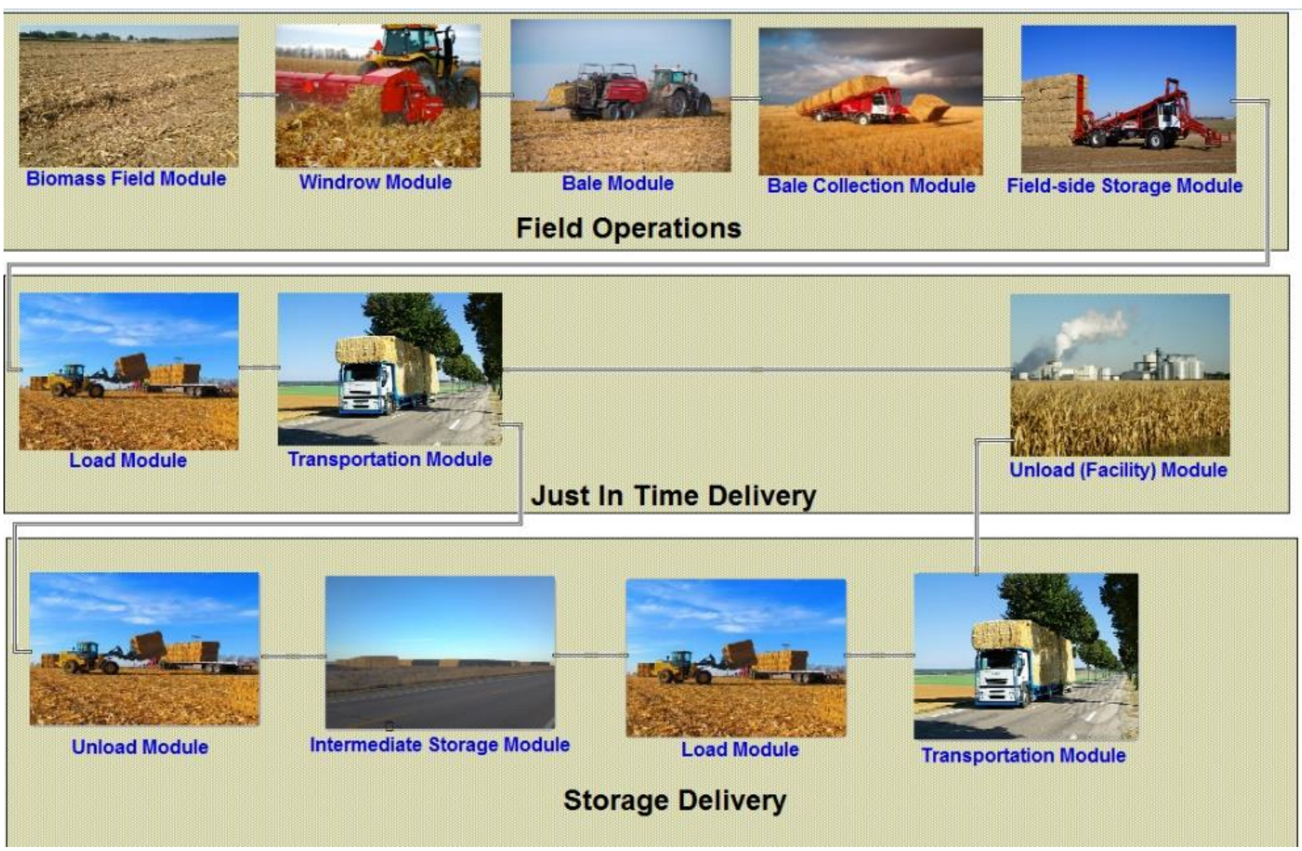
(3) Post-harvest season after planting/ Storage delivery: This period of time covers the reminder of the year when fields are not available as the next crop growing season commences. During this period, sufficient amount of stover inventory has been built up at the intermediate storage sites during the harvest and transportation seasons. Bales at the intermediate storage sites may have to be stored for several months before being delivered to the biorefinery. The bale stacks are stored on a well-drained rocked surface and covered by tarps to protect them against the environment and minimize dry matter losses (Hess et al., 2009). Other storage options such as open or closed sheds are not considered in this analysis. It is assumed that there is no carry-on inventory to the next year and all the stored inventory in the intermediate storage sites are consumed by the bio-conversion facility in the same year. The logistics operations during this period include intermediate storage, loading, transportation and unloading at the bio-conversion facility.

The corn stover logistics scenario being considered in this study is developed based on the existing bale logistics practices used by the pioneering cellulosic ethanol plants in the United States (Li et al., 2012; DuPont. 2016). These plants use corn stover as feedstock for the production of cellulosic ethanol.

Output data: The outputs of IBSAL-MC are tailored based on the objectives of this study. These outputs include: (1) Operating cost of each logistic operation and the distribution of corn stover delivered cost, (2) Size of the harvest area and the number of contracted fields, (3) number of required logistic machinery fleet, its associated capital cost and the number of operators to run this machinery fleet and (4) Size of the intermediate storage site and its inventory level.



a. The simulated logistics system has three time periods: (1) Harvest season, (2) Roadside bale removal and transportation season and (3) Post-harvest season after planting.



b. Simulation of the supply chain system

Figure 4. 4. The structure of simulated corn stover logistics system in IBSAL-MC

4.4 Results

In this chapter, three biorefinery sizes are considered for the proposed facility to quantify the size of the required logistical resources given the local conditions of the supply area. These biorefinery scenarios include a large-sized biorefinery (310,000 dt/year or 860 dt/day), a mid-sized one (187,200 dt/year or 520 dt/day), and a small-sized one (63,000 dt/year or 175 dt/day). These biorefinery scenarios are refereed as LS, MS and SS, respectively, in the reminder of this paper. The biorefinery size in the LS and SS scenarios was estimated based on the assumption of a base price of $400/tonne for cellulosic sugar and a target Return on Investment (ROI) of 15% over 10 years. The average conversion yields of the bio-conversion facility are assumed to be 46% and 36% for cellulosic sugar and lignin on a weight basis, respectively. Lignin is the co-product of the conversion process with an estimated market price of $40/tonne (Oo & Lalonde, 2012; Marchand, 2015; personal communication with Bioindustrial Innovation Canada (BIC) Inc., November 20, 2015). The cellulosic sugar plant is assumed to have a ramp-up period of 18-24 months before reaching a steady state. To achieve the target ROI, the delivered stover cost at the gate of the sugar plant is estimated to be $81.33/dt. It is noted the mid-sized facility is considered for the comparison purpose and is estimated as the average of the LS and SS scenarios. Since several input parameters are considered to be variable, multiple simulation runs are carried out in order to capture the impact of the variable input parameters on the IBSAL-MC outputs, in particular the delivered costs. To this end, the IBSAL-MC model was run for 200, 250 and 300 replications for the SS, MS and LS scenarios, respectively.

4.4.1 Harvest area and contracted fields

Figure 4. 5. Changes in the required supply area in three biorefinery scenarios

Figure 4.5 shows the covered supply area for each biorefinery size in comparison to the total corn stover supply available in the four considered counties. As shown in Figure 4.5, about 18.9%, 56.5% and 92.9% of the total corn fields in the supply area (i.e. acres) need to be contracted to meet the annual biomass demand of the SS, MS and LS biorefinery scenarios, respectively.

Table 4.1 lists the summary of the obtained results on the required supply area for each biorefinery scenario. As shown in Table 3.1, the average distances between corn fields and the facility are estimated to be 53 km, 73 km and 98 km in the SS, MS and LS scenarios, respectively. The expansion of the supply area leads to the increase in the number of contracted corn fields. It is estimated that 343, 972 and 1,579 corn fields need to be contracted in the SS, MS and LS scenarios, respectively. The corn field sizes are in the range of 30 to 1,385 acres with an average size of 142 acres. The increase in the number of contracted corn fields can result in the increase in administrative costs spent on securing short term or long-term contracts with local corn growers and also the managerial supports for a smooth functioning of the logistics system (Hess et al., 2009). These administrative and managerial costs are not captured in the IBSAL-MC model as they depend on the developed supply contract agreement by the biorefinery and the willingness of the corn growers to participate in the supply system. The development of the contract agreement and its impact on the delivered costs are outside the scope of this chapter. This issue can be studied in later chapters.

Table 4. 1. Obtained results on the corn stover supply area for three biorefinery scenarios

Biorefinery scenario	SS	MS	LS
Harvest area (ac)	45,800	137,000	225,400
Average distance between fields and the plant (km)	53	73	98
Number of contracted corn fields	343	972	1,579
Average size of contracted corn fields (ac)	134	141	142
Average harvestable corn stover yield (dt/ac)	1.73	1.72	1.72

4.4.2 Required logistic equipment and workforce

The IBSAL-MC model estimates the number of the required logistics equipment for each logistics operation based on five factors: (1) daily biomass demand of the biorefinery; (2) length of the harvest season (the first period in Figure 2); (3) length of the transportation period from corn fields to the intermediate storage site and the facility (the second period in Figure 2); (4) daily working hours; and (5) required time to mobilize logistics equipment between corn fields. Table 3 shows the estimated number of logistics equipment, their economic values and the number of operators to run this equipment fleet. The total number of operators is estimated to be 37, 136 and 235 in the SS, MS and LS scenarios, respectively. Out of these jobs, 30, 107 and 179 jobs are seasonal, which involve field operations, loading and transportation at the roadside of the contracted corn fields during harvest and transportation seasons (the first and second periods in Figure 2). The remaining jobs take care of year-round storage, loading, unlading and transportation operations.

The total number of the logistic equipment in the corn stover supply system is estimated to be 54, 190 and 321 units in the SS, MS and LS scenarios, respectively. The economic values of these units are estimated based on the assumption that all the equipment used in the corn stover supply system are brand new (Gutesa, 2013, personal communication with AGCO Inc., April 24, 2016). It is assumed that the biorefinery owns the equipment fleet to run the field operations, loading/unlading at the storage site and the flatbed trailers and trucks to transport bales from the storage site to the biorefinery. The additional flatbed trailers, trucks and loaders used during the harvest and transportation seasons to handle and transport bales either to the storage site or to the facility are assumed to be contracted out. The total required capital investment for establishing a dedicated logistics fleet is estimated to be $6.72, 21.83 and 35.51 million in the SS, MS and LS scenarios, respectively. Thus, the increase in the equipment capital investment from the SS scenario to the MS and LS scenarios are estimated to be 233% and 428%, respectively.

The economic values in Table 4.2 reflect the maximum required upfront capital investment for a dedicated brand-new logistics fleet. However, local farmers and custom harvester groups may manage a portion of this fleet. They can use the harvest equipment that they already own for harvesting hay or other biomass types such as wheat straw if there is no conflict in the harvest seasons. However, the existing equipment fleet owned by local farmers or custom harvest groups must meet the performance and quality specifications of the cellulosic sugar plant such as bale size, bale density, ash content and field efficiency.

Table 4. 2. Number of logistics equipment, their economic values and the number of operators to run the logistics equipment

Equipment	SS scenario			MS scenario			LS scenario		
	Number of machines	Economic value ($)	Number of operators	Number of machines	Economic value ($)	Number of operators	Number of machines	Economic value ($)	Number of operators
Cornstalk shredder	7	245,000	-	23	805,000	-	38	1,330,000	-
Square baler	7	980,000	-	22	3,080,000	-	36	5,040,000	-
Bale collector/stacker	7	1,750,000	7	23	5,750,000	23	38	9,500,000	38
Tractor (185-220 hp)	14	2,800,000	14	45	9,000,000	45	74	14,800,000	74
Telescopic bale loader- roadside of corn fields	3	-	3	16	-	16	28	-	28
53-ft flatbed trailer truck- roadside of corn fields	9	-	9	36	-	36	65	-	65
Telescopic bale loader- intermediate storage site	3	270,000	3	13	1,170,000	13	26	2,340,000	26
53ft-flatbed truck- intermediate storage site	3	585,000	3	9	1,755,000	9	12	2,340,000	12
Telescopic bale loader- cellulosic sugar facility	1	90,000	1	3	270,000	3	4	360,000	4
Total	54	6,720,000	37	190	21,830,000	136	321	35,710,000	235

4.4.3 Storage size, inventory level and the daily number of truckloads

As shown in Figure 4.6, the corn stover inventory is built up for 110-120 days (i.e. mid-October to mid-February). During this period of time, corn stover is harvested and the collected bales are transported either to the cellulosic sugar plant or to the intermediate storage site. Thus, the maximum inventory level is achieved at the end of this period. Thereafter, the inventory level begins to drop gradually as stored bales are transported from the intermediate storage site to the biorefinery according to its daily biomass demand. The observed change in the inventory level through the year is fairly the same for all three biorefinery scenarios.

Based on the observed maximum inventory level and the storage configuration listed in Table 4.3, the size of the intermediate storage site is estimated to be 42.6 acre (92,596 bales), 144.4 acre (291,763 bales) and 233.5 acre (464,903 bales) in the SS, MS and LS scenarios, respectively. Thus, the inventory level and the land requirement for storage in the MS and LS scenarios are 225% and 425% greater than those of the SS scenario. The increased biomass inventory level could increase the fire risk at the intermediate storage site (Martinez-Kawas, 2013).

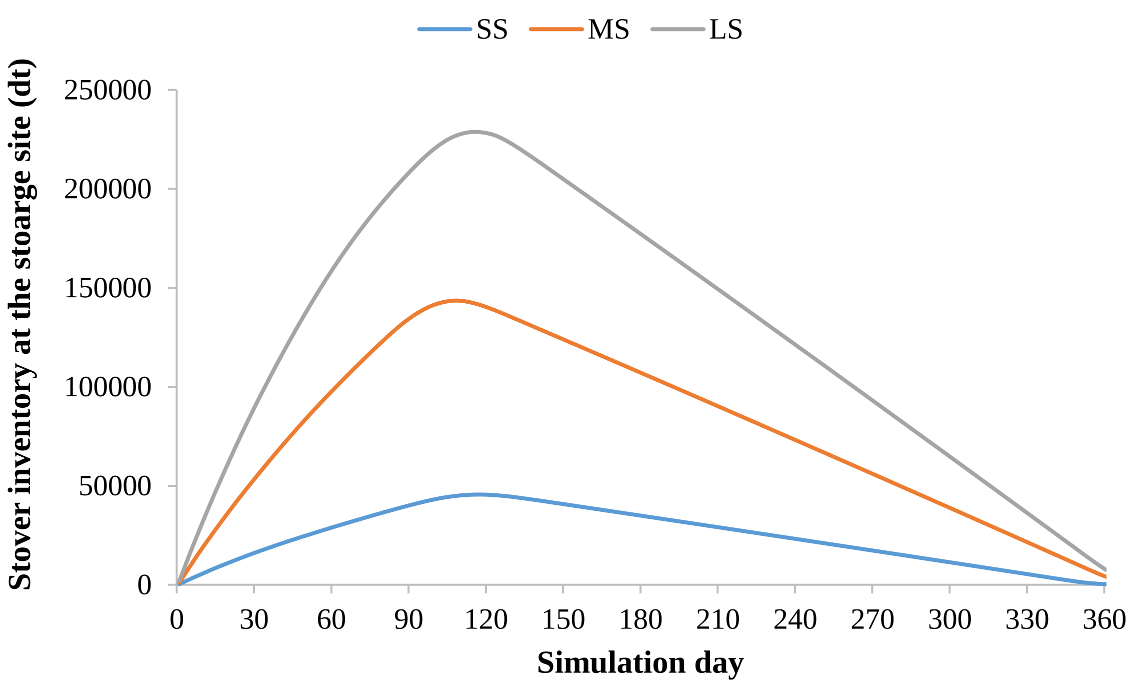


Figure 4. 6. Stover inventory build-up at the intermediate storage site for three biorefinery scenarios. The start of the simulation year is assumed to be mid-October when corn stover harvest begins in the considered case study

Table 4. 3. Intermediate storage configuration

Biorefinery scenario	SS	MS	LS
Maximum inventory (dt)	45,563	143,564	228,759
Number of stored bales	92,596	291,763	464,903
Stack configuration (bales)[50]	6 high, 6 wide and 60 long		
Number of stacks	47	136	216
Clearance between stacks (m)*	30.5		
Total storage footprint (ac)	42.6	144.4	233.5

**Personal communication with Bioindustrial Innovation Canada (BIC) Inc., November 20, 2015*

The development of a well-located storage site, the land preparation for the year-round accessibility by incoming and outgoing trucks and reliable functioning conditions inside the storage site is another upfront capital and administration cost for the bio-conversion facility. In addition, the increased number of incoming and outgoing trucks to/from the storage site can complicate the storage management for a large-scale facility.

Figure 4.7 shows the total number of truckloads delivered to the biorefinery and the intermediate storage site during three time periods in an operational year. Each truckload contains 39 bales with a payload of 17.5-20.80 dt depending on the moisture content and the amount of dry matter losses in bales during the storage time. Number of truckloads shows the intensity of the truck traffic within the supply area. From mid-October to mid-January, a large number of truckloads transport bales from corn fields to the storage site. From mid-January to mid-February, stover harvest and collection operations end and the remaining stored bales at the roadside of corn fields are transported to the intermediate storage site and the facility. For the rest of the year, the stacked bales at the intermediate storage site are transported to the facility at a constant daily rate because the daily biomass demand of the facility is assumed to be constant throughout the year. Total number of incoming or outgoing truckloads at the storage site is estimated to be 2,776, 8,099 and 13,259 in the SS, MS and LS scenarios, respectively. The estimated number of truckloads are comparable to those of Gutesa (2013).

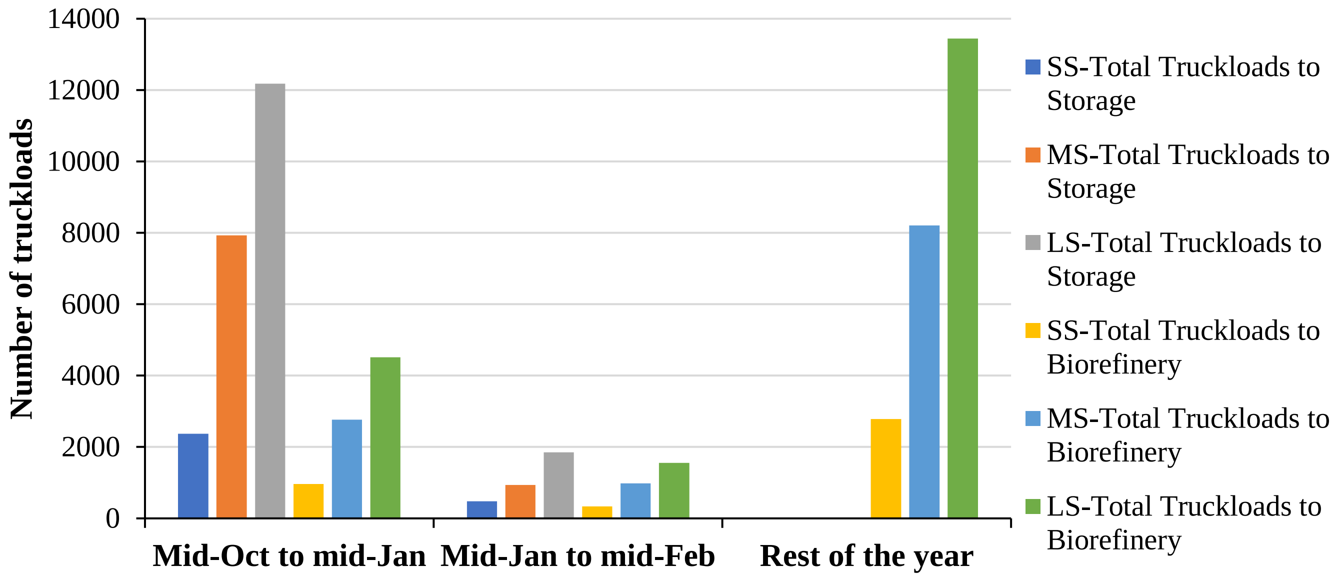


Figure 4. 7. Total number of truckloads delivered to the bio-conversion facility and the intermediate storage site

The large number of truckloads handled and transported during the short harvesting window calls for a large number of loading and transportation equipment compared to the rest of the year, as shown in Table 4.3. While the daily stover demand increases by 197% and 391% from the SS scenario to the MS and LS scenarios, respectively, total number of truckloads from mid-October to mid-February at the roadside of corn fields increase by 204% and 384%.

4.4.4 Delivered Cost

Table 4.4 shows the details of the average delivered cost for the SS, MS and LS scenarios, respectively. The average corn stover delivered costs are estimated to be \$82.09/dt, \$87.49/dt and \$93.75/dt in the SS, MS and LS scenarios, respectively. The primary reason behind the increased delivered costs from the SS scenario to the MS and LS scenarios is the transportation cost, as shown in Table 4.4. The average distance between corn fields and the bio-conversion facility is estimated to be 53 km, 73 km and 98 km in the SS, MS and LS scenarios, respectively. In addition, the maximum distance is estimated to be 71 km, 104 km and 175 km. Since other operations, such as shredding, baling, and bale collection take place in similar conditions within the corn fields, the differences between other operating costs are insignificant. It is noted that nutrient replacement cost is the compensation paid to the corn growers for nutrients (N, P, K) in the corn stover removed from a corn field. The obtained logistics costs are comparable with those of (Shah, 2013; Martinez-Kawas, 2013; Duffy & Marchand, 2013).

Table 4. 4. Average operating costs of the corn stover logistics operations

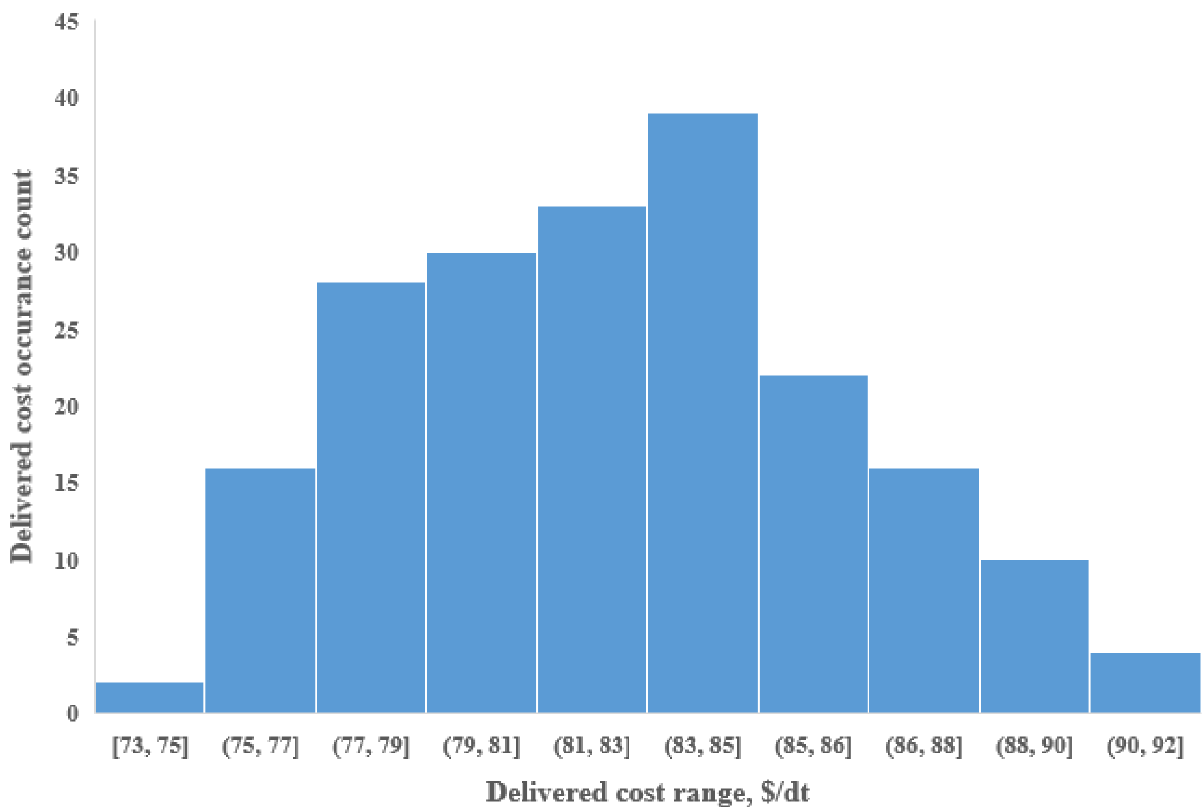
Cost component ($/dt)	SS scenario	MS scenario	LS scenario
Nutrient replacement	12.05	12.05	12.05
Shred and windrow	7.42	7.59	7.77
Bale	17.36	17.66	17.68
Bale collection/stack at the roadside	8.66	8.92	8.98
Load at the roadside	2.11	2.28	2.30
Transportation to the intermediate storage	26.62	34.39	42.81
Load & unload at the intermediate storage	1.66	1.70	1.77
Intermediate storage	9.09	9.37	9.80
Transportation to the bio-conversion facility	14.32	14.12	14.04
Unload at the facility	1.10	1.08	1.06
Total delivered cost	**82.09**	**87.49**	**93.75**

Table 4. 5. Summary of the results of corn stover delivered cost

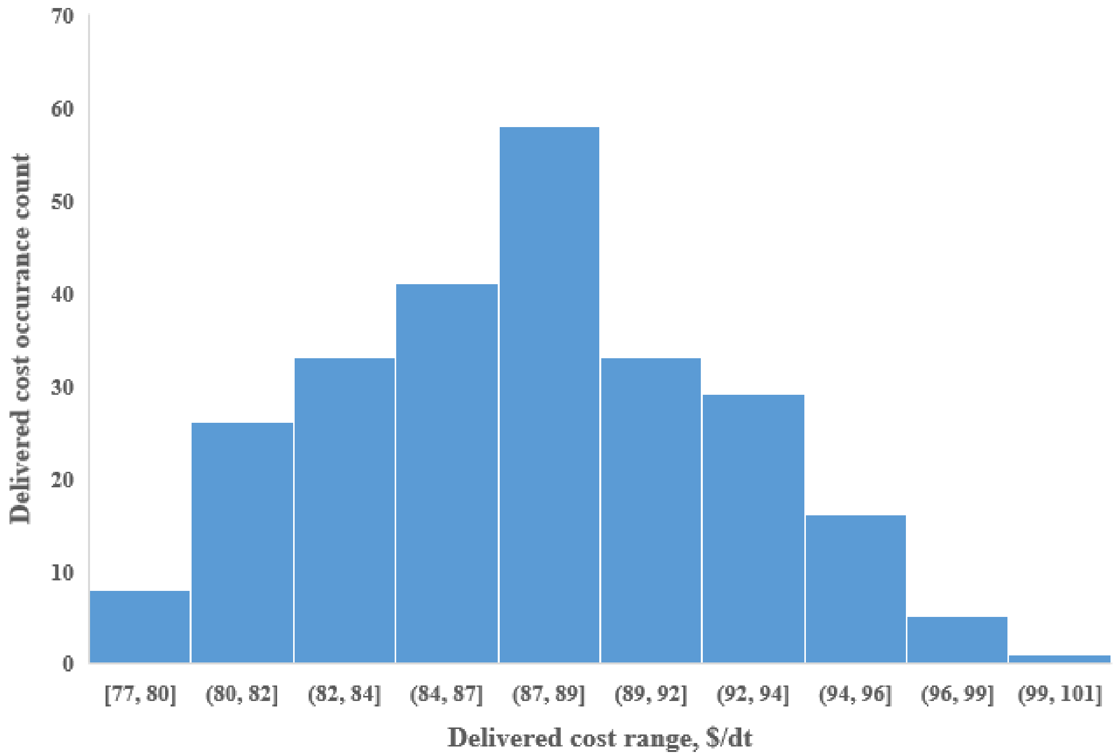
Biorefinery scenario	SS	MS	LS
Number of simulation runs	200	250	300
Maximum observed value ($/dt)	92.38	101.08	107.79
Average observed value ($/dt)	82.09	87.49	93.75
Minimum observed value ($/dt)	72.76	77.24	79.19
Standard deviation ($/dt)	3.97	4.56	5.18
Confidence interval	90%	90%	90%
Margin of error ($/dt)	<0.50	<0.50	<0.50
Probability of achieving the target delivered cost	45.5%	9.2%	0.3%

Figure 4.6 and Table 4.5 show the distributions of the corn stover delivered costs for three biorefinery scenarios. As the size of the biorefinery increases, the standard deviation of delivered

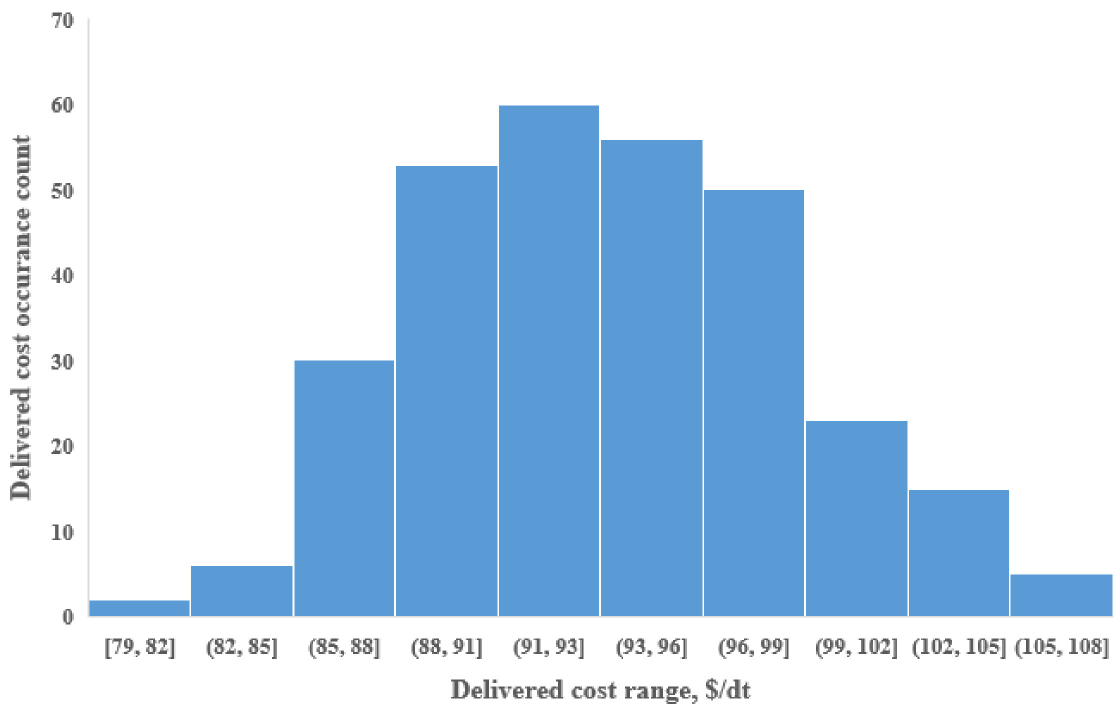
cost increases as well. This indicates that a larger supply system could encounter more variability due to the increase in the harvest area, transportation distances, the number of contracted fields and their biomass yield and also the unproductive time of the logistics operations as they need to move between fields in a larger supply area. Based on the observed delivered cost distributions, the probabilities of meeting the target corn stover delivered cost (i.e. $81.33/dt) are estimated to be 45.5%, 9.2% and 0.3% in the SS, MS and LS scenarios, respectively.



a. SS scenario (175 dt/day)



b. MS scenario (520 dt/day)



c. LS scenario (860 dt/day)

Table 4. 6. Distribution of the stover delivered cost for three biorefinery scenarios

4.4.5 Sensitivity Analysis

Results from previous sections were developed for a base case corn stover logistics scenario in which three input parameters were assumed to be constant including the number of working days during the harvest season, the realized corn yield at corn fields and the farm participation rate. The number of working days was assumed to be 90 days. However, Figure A3 implies that the number of working days could be in the range of 70-80 days based on the recorded weather data in the period of 2006-2015. In addition, the realized corn yield in the supply area varies with a standard deviation of 14.7 bu/ac. Finally, the farm participation rate was assumed to be 100% in the base case scenario which is unlikely in a real case. Thus, a sensitivity analysis is conducted to study the impact these input parameters have on the obtained results in the base case scenario.

Table 4.7 summarizes the sensitivity of the simulation results to the changes in the number of working days in the harvest season. The main impact is observed in the number of required logistical equipment and its associated capital investment. As expected, a shorter harvest season calls for more logistics equipment. The magnitude of the impact depends on the distribution of corn fields in the supply area. Thus, the impact on three biorefinery scenarios is not the same as the corn stover is not distributed evenly in the supply area. As mentioned before, the maximum distance is estimated to be 71 km, 104 km and 175 km in the SS, MS and LS scenarios, respectively, and the majority of corn stover is located 60-170 km from the bio-conversion facility.

The number of working days has no impact on the harvested area and the number of contracted corn fields as the same amount of corn stover from the same corn fields is processed in the cases of 70 and 80 working days as in the base case. Although the same amount of corn stover is harvested and collected at the roadside of corn fields in three cases of 70, 80 and 90 working days, more corn stover would be stored at the roadside as the harvest season shortens. Thus, less amount of corn stover would be transported to the intermediate storage site, as shown in Table 3.6. In addition, the change in the delivered cost is not significant since each piece of equipment operates fairly the same number of hours during the harvest season in all three cases of 70, 80 and 90 working days.

Table 4. 7. Sensitivity analysis on the number of working days in the harvest season

Number of working days in the harvest season	80 days			70 days		
Biorefinery scenario	SS	MS	LS	SS	MS	LS
Change in the simulation outputs compared to the base case logistics system						
Number of logistics equipment fleet	+5.0	+8.0	+9.0	+10.0	+20.0	+18.0
Total economic value of the logistics equipment fleet (%)	+11.8	+9.9	+4.3	+23.6	+18.4	+8.6
Harvested area (%)	0	0	0	0	0	0
Number of contracted corn fields (%)	0	0	0	0	0	0
Maximum Inventory (%)	0	-6.6	-1.0	-1.2	-6.1	-1.3
Storage size (%)	0	-6.9	-1.0	-2.6	-7.0	-1.5
Delivered cost (%)	+1.3	+3.0	+0.2	+0.6	+2.0	+1.2

The sensitivity of the simulation results to the changes in the corn yield are shown in Table 4.8. The corn yield impacts the amount of corn stover available for harvesting in corn fields. In the case of 15 bu/ac reduction in the considered corn yields in the base case scenario, the annual stover demand of the bio-conversion facility would not be met in the MS and LS scenarios. The total unfulfilled biomass demand is estimated to be 28,000 dt and 181,000 dt, respectively. Due to these shortfalls, the changes in the obtained results are not provided for these two cases in Table 4.8 as they cannot be compared with other cases in which the annual biomass demand is met. Changes in the corn yield also impact the size of the harvest area, the number of contracted fields and the transportation distance. In the case of 15 bu/ac increase, the average transportation distance is reduced by 13.2%, 15.1% and 23.5% in the SS, MS and LS scenarios, respectively, compared to the base case scenario. This results in the reduction in the number of transportation equipment. The number of field equipment slightly decreases since the field equipment harvests and collects the same amount of stover in a smaller harvested area in the same harvest period.

The change in the size of the supply area also impacts the stover delivered cost. The increase in the corn yield by +15 bu/ac reduces the delivered costs by 4.6%, 4.1% and 7.3% in the SS, MS, LS scenarios, respectively, compared to the base case scenario. Thus, the probabilities of achieving the target delivered cost increase from 45.5%, 9.2% and 0.3% to

80.0%, 30.0% and 8.9% in the SS, MS and LS scenarios, respectively. In contrast, a reduction of 15 bu/ac in the corn yield decreases this probability from 45.5% to 12.0% in the SS scenario.

Table 4. 8. Sensitivity analysis on the corn yield

Change in the corn yield (bu/ac)	+15			-15
Biorefinery scenario	SS	MS	LS	SS
Change in the simulation outputs compared to the base case logistics system				
Number of logistics equipment fleet	-5.0	-29.0	-45.0	+8.0
Total economic value of the logistics equipment fleet (%)	-10.5	-14.3	-14.6	+10.8
Harvested area (%)	-5.1	-5.1	-4.8	+6.3
Number of contracted corn fields (%)	-6.1	-8.9	-3.8	+3.5
Average transportation distance (%)	-13.2	-15.1	-23.5	+21
Maximum Inventory (%)	-1.3	-5.5	-0.5	+3.8
Storage size (%)	0	-6.1	-0.5	+0.5
Delivered cost (%)	-4.6	-4.1	-7.3	+5.0

Table 4.9 summarizes the sensitivity of the simulation results to the changes in the farm participation rate. The annual biomass demand of the bio-conversion facility is not met in the LS scenario at 75% and 50% farm participation rates. The amount of unfulfilled demand is estimated to be 75,500 dt and 180,000 dt in these rates, respectively. In the MS scenario, about 2,000 dt of the annual biomass demand cannot be met at 50% farm participation rate. The minimum farm participation rates required to meet the annual biomass demand are estimated to be 57% and 91% in the MS and LS scenarios, respectively.

The results in Table 4.9 are only provided for the cases in which the annual biomass demand is met. Similar to the corn yield, changes in the farm participation rate impact the size of the harvest area, number of contracted fields and the transportation distances. However, as mentioned before, the magnitude of the impact depends on the distribution of corn fields, their sizes and corn stover yields in the supply area. As shown in Table 4.9, at 75% farm participation rates, the average transportation distance increases by 5.7% and 16.4% in the SS and MS scenarios, respectively, compared to the base case scenario. It increases by 18.9% in the SS scenario compared to the base case scenario at 50% farm participation rate. The probabilities of achieving the target stover delivered cost drop from 45.5% and 9.2% to 36.3% and 1.3% in the SS and MS scenarios, respectively, at 75% participation rate. It also reduces from 45.5% to 18.3% in the SS scenario at 50% farm participation rate.

Figures 4.8 and 4.9 show the changes in the size of the supply area and the harvested acreage of corn fields per grid as a result of changes in the realized corn yield and the farm participation rate in the SS scenario. These figures are in agreement with the reported harvested area and maximum transportation distance between corn fields and the facility in Tables 4.8 and 4.9.

Table 4. 9. Sensitivity analysis on the farm participation rate

Change in the farm participation rate	-25%		-50%
Biorefinery scenario	SS	MS	SS
Change in the simulation outputs compared to the base case logistics system			
Number of logistics equipment fleet	0	+5	+10
Total economic value of the logistics equipment fleet (%)	0	+3.7	+15.7
Harvested area (%)	+2.2	0	+0.4
Number of contracted corn fields (%)	-1.6	-1.5	-5.4
Average transportation distance (%)	+5.7	+16.4	+18.9
Maximum Inventory (%)	+4.40	+4.60	+4.40
Storage size (%)	+5.20	+5.30	+5.20
Delivered cost (%)	+1.40	+3.60	+4.00

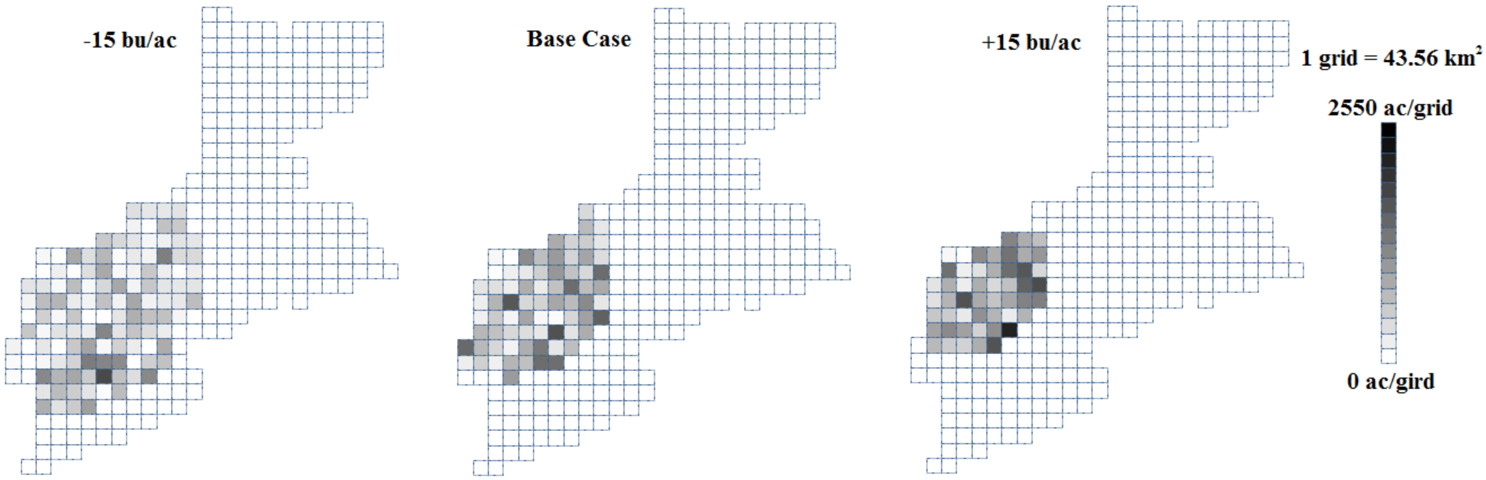


Figure 4. 8 Sensitivity of the supply area to changes in the corn yield (SS scenario)

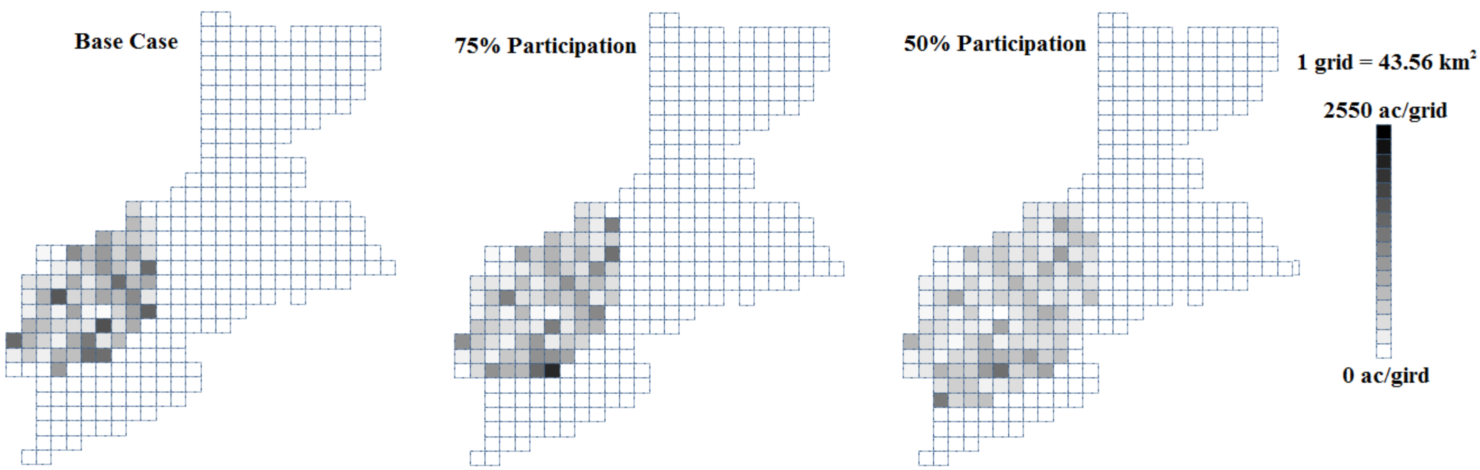


Figure 4. 9. Sensitivity of the supply area to changes in the farm participation rate (SS scenario)

4.5 Discussion

From a biomass logistics standpoint, the delivered cost of biomass to a biorefinery has been the main factor considered to evaluate the economic viability of the biorefinery along with other factors such as the profile of the bio-conversion technology, the market price of the final and co-products and supporting policies such as subsidies and financial incentives. However, the biomass delivered cost does not reflect the size of the required logistical resources and the complexity of the logistics system. These logistical resources are required to mobilize large quantities of biomass from biomass fields to the gate of the biorefinery. They can impact the long-term economic success of a biorefinery project given the local characteristics of the biomass supply area. The obtained results show that the harvest area and the number of contracted corn fields are the logistical resources that their sizes increase as the size of the biorefinery increases to meet the annual biomass demand. In the considered case study, the size of the harvest area and the number of contracted fields increase by 65% and 78% from the SS scenario to the MS and LS scenarios, respectively. The biorefinery incurs administrative and managerial costs to secure and contract the required supply area and the biomass growers and to support the overall logistics system for a smooth functioning. These costs are part of the upfront costs that a biorefinery should consider in its economic analysis.

The average stover delivered costs are estimated to be $82.09/dt, $87.49/dt and $93.75/dt in the SS, MS and LS scenarios, respectively. The increase in the required capital costs to develop a dedicated logistics equipment fleet is estimated to be much greater than the increase in the delivered costs as the size of the biorefinery increases. The upfront capital costs are estimated to be $6.72, 21.83 and 35.51 million in the SS, MS and LS scenarios, respectively. The high capital cost of the logistics equipment fleet could complicate the financial support for the establishment of a large-scale biorefinery. In addition, the standard deviation of the corn stover delivered cost is the highest in the LS scenario. A high standard deviation reflects the decreased probability of achieving the target delivered cost and the ROI considered in the business model of a biorefinery. The probability of achieving the target corn stover delivered cost is estimated to be 45.5%, 9.2% and 0.3% in the SS, MS and LS scenarios, respectively.

To run the logistics equipment fleet efficiently, 37, 136 and 235 well-trained operators are required in the SS, MS ad LS scenarios, respectively. Most of these operators are required during the short harvest season. Hiring large number of well-trained labors for such a short period of time could be challenging, especially if the harvest season overlaps with other agricultural operations in the supply area.

The last considered logistics resources are the size of the intermediate storage site and its inventory level. The obtained results show that the inventory level and the land requirement for storage in the MS and LS scenarios are 225% and 425% greater than those of the SS scenario. The development of a well-located storage site and the land preparation for the year-round accessibility by incoming and outgoing trucks and also reliable functioning conditions inside the storage site are other upfront capital and administration costs for a biorefinery. These costs increase with the increased size of the biorefinery. In addition, the high level of biomass inventory complicates the storage management and calls for effective measures to reduce the file risk in bale stacks and the associated insurance costs. In addition, the number of incoming and outgoing trucks to/from the storage site can complicate the storage management for a large-scale facility. Total number of incoming or outgoing truckloads at the storage site is estimated to be 2,776, 8,099 and 13,259 in the SS, MS and LS scenarios, respectively.

The sensitivity analysis is conducted to measure the impact of three input parameters on the corn stover supply system in the base case scenario. The parameters are the number of working days in the harvest season, the realized corn yield and the farm participation rate. Number of working days mainly impact the number of required logistics equipment to finish the field operations. In contrast, both corn yield and farm participation rate impact the entire logistics system as these two parameters impact the availability of corn stover in the supply area. The obtained results show that the annual biomass demand of the biorefinery would not be met in both MS and LS scenarios in the case of 15 bu/ac reduction in the corn yield. In both cases of 75% and 50% farm participation rates, the annual biomass demand would not be met in the LS scenario. In contrast, the annual biomass demand would not be met only at 50% farm participation rate in the MS scenario. In addition, these two parameters impact the probability of achieving the target delivered cost. The increased corn yields and farm participation rates reduce the number of required logistical resources and increase the probability of meeting the target biomass delivered cost.

4.6 Conclusion

The obtained results show that the long-term economic viability of a biorefinery project is impacted by the magnitude of the required logistical resources and their associated upfront and administrative costs. In addition, the managerial support to run the logistics system and to contract suppliers can also impact the long-term economic success of a biorefinery. Finally, the magnitude of the sensitivity of the logistical resources to the main input parameters can be used to evaluate the level of risk to meet the target delivered cost and the ROI and then develop effective mitigation strategies accordingly. It is noted that the impact of the biorefinery size on the required logistical resources depends on the local characteristics of the supply area. Thus, the magnitude of the impact and the level of complexity could change from region to region.

The limitation of the analysis conducted in this chapter is that the analysis focused entirely on the supply side of the biorefinery's operation while the fluctuation in the product's market price is not addressed. Unless there exists a long-term consumer of the product at an agreed fixed price, a complete economic performance and risk analysis needs to address variabilities in the supply chain parameters as well as product's market price fluctuation. In the next chapter, a quantified economic performance and risk analysis approach is applied to achieve this.

Chapter 5. A Risk Analysis Approach to Evaluate the Economic Performance of a Biorefinery and to Quantify the Economic Incentives for Participating Biomass Producers

5.1 Synopsis

In the last chapter, the level of complexity in a biorefinery's supply system and its importance to the economic well-being of the biorefinery have been investigated. However, a biorefinery also faces economic risks associated with the market price volatility of its products. While existing relevant studies have considered variation in a number of supply chain parameters, the market price volatility of the products was rarely included in the risk assessment for biomass projects. As a result, the economic incentives for increasing the farm participation rate is hard to be quantified and often evaluated through survey data. In this chapter, a quantified approach is developed to analyze the impacts to the economic wellbeing of a biorefinery, to visualize the results through modified risk heat map to facilitate communication and to quantify the amount of economic incentives potentially exists for participating biomass producers.

5.2 Objectives and Contributions

Investment in emerging biomass ventures has been increasing in the last decade, mainly to decarbonize the energy sector. The early development of such ventures has shown potential environmental, social, energy security and economic benefits. However, the steady growth of these biomass projects has been hindered by risks arising from technical and non-technical obstacles (Elghali et al., 2007; Sultana et al., 2010; Giuntoili et al., 2013; Arnold & Yildiz, 2015; Miranda et al., 2015). For biomass ventures, volatility in the biomass supply and the market price of final products accounts for the highest risk among non-technical barriers to investors and institutional lenders (Yue et al., 2014; Abbati de Assis et al., 2017).

Despite the evaluation of farm participation rate in the literature, there is a lack of discussion on quantifying the combined impact of variability in farm participation rate and volatility in the product market price on the overall economic performance of a biorefinery. While previous studies considered variation in a number of supply chain parameters, the price volatility of final products was rarely included in the risk assessment. In addition, the economic incentives for increasing the farm participation rate is often evaluated through survey data instead of biomass supply chain analysis in which the economic incentives are estimated based on the biomass delivery cost and the expected profit of the biorefinery. In this chapter, an approach is developed to: 1) evaluate the economic performance of a biorefinery project given the volatility in the market price of the final product and the variability in the biomass delivered cost, and 2) quantify the potential economic incentives for participating biomass producers. Return on Investment (ROI) is used as the basis to quantity the maximum amount of incentives that can be provided to biomass producers. In addition, a modified risk heat map is used to visualize the expected ROIs for various combinations of the market price of the final product and the biomass delivered cost. The results and their visualization through the modified risk heat map can facilitate and promote the discussion on the development of risk mitigation strategies and potential business relationship between biorefineries, investors and biomass producers. No published work, to our knowledge, has applied the risk heat map to visualize the quantified impact of farm participation rate and product price on the overall economic benefits of a biorefinery and the amount of incentive available to biomass producers.

5.3 Methodology

5.3.1 Methodology Outline

Figure 5.1 shows the developed methodology to (1) evaluate the economic performance of a biorefinery given the variability in the market price of the final product and biomass cost, (2) visualize the economic benefits and risks to facilitate communication and (3) quantify the potential economic incentives for biomass suppliers. The developed methodology has the following six steps:

Step 1. Develop the base case scenario for a biorefinery: The base case scenario is developed based on a target ROI, average market value for the final product and co-product(s), annual production capacity, production cost, annual biomass demand and a target biomass cost at the gate of the biorefinery. These parameters could be the outcome of a techno-economic analysis. In this study, the base case scenario is developed based on available data from an under-construction cellulosic sugar plant in Southwestern Ontario, as described in the next section.

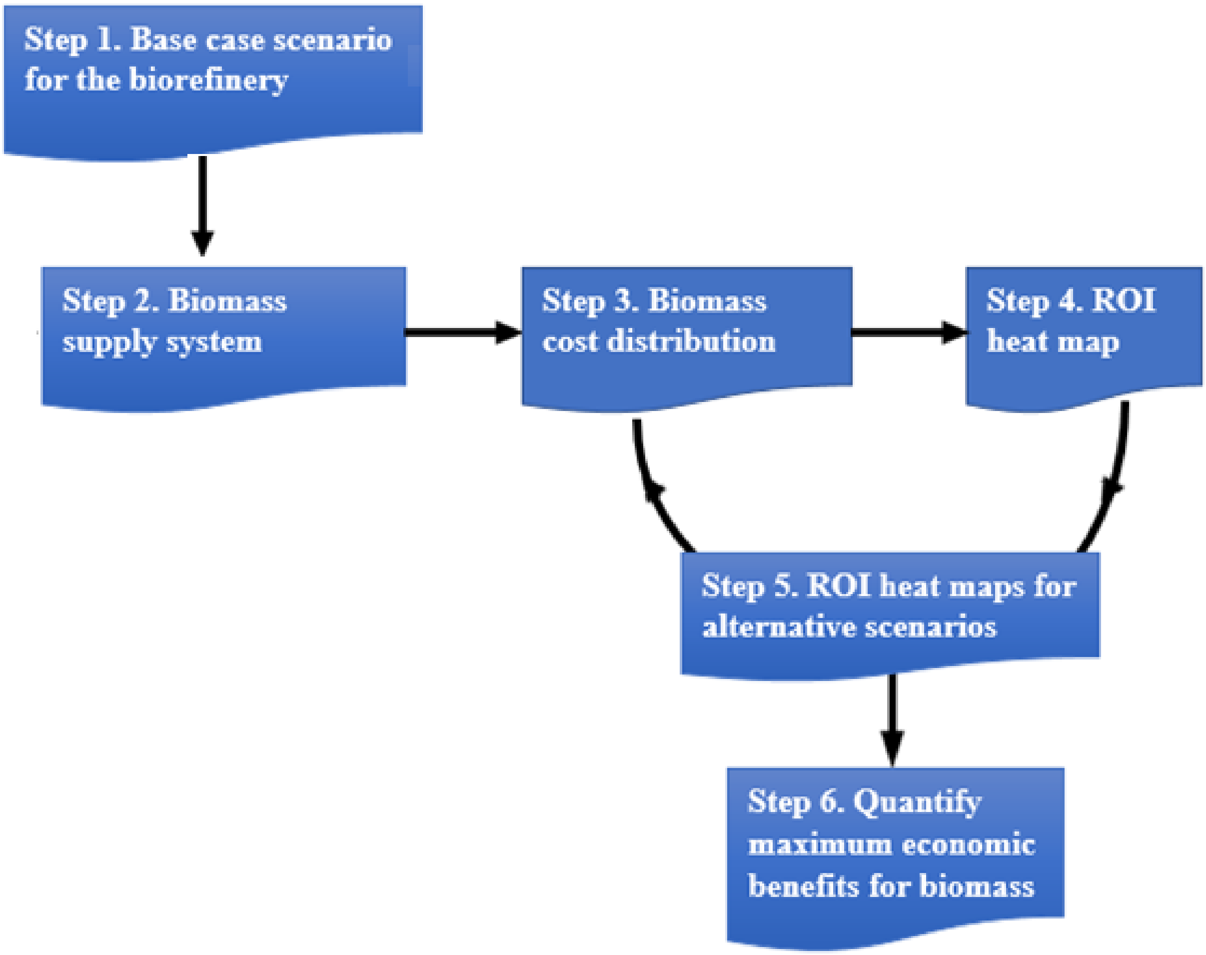


Figure 5. 1. The developed methodology to quantify the economic benefits and incentive to biomass suppliers from increased farm participation rate.

Step 2. Develop the biomass logistics system: The biomass logistics system is developed based on the local conditions of the supply area such as the distribution of biomass producers in the supply area, farm participation rate, field size, biomass yield, the existing logistics infrastructure, harvest window and weather conditions. The details of the biomass supply area and the logistics equipment are collected in this step. Some of the input parameters are considered as variables to reflect the temporal and spatial variations in the supply system. These parameters include biomass yield, biomass moisture content, bale bulk density, dry matter loss, equipment capacity and efficiency, machine breakdown and repair times, winding factor and road transportation time.

Step 3. Develop the biomass delivered cost distribution: It is often challenging to maintain the biomass logistics cost at a level that supports the profitability of a biorefinery, especially when it is not possible to maintain the required supply of biomass and to manage the variability in logistics parameters such as weather conditions, harvest window, moisture content, and equipment field efficiency. This usually leads to a range of delivered costs in real cases. The estimation of this range requires capturing the dynamics and complexity of biomass logistics systems. In this study, the Monte Carlo simulation model, IBSAL-MC, is applied to develop the biomass cost distribution.

Step 4. Develop a ROI heat map: This step determines the probability of meeting the target ROI considered in Step 1 and the expected ROI based on the variability in both biomass delivered cost and market price of the final product. A heat map is a communication tool used in the risk assessment process to highlight major risks and promote discussion on the mitigation strategies. Figure 5.2 shows an example of the heat map to identify the major risks in a system. The horizontal axis shows the likelihood of a given risk occurring, the vertical axis shows the potential impact that the risk will have on the system objective and the colours show the severity of the risk (e.g., green: low severity, yellow: medium severity and red: high severity).

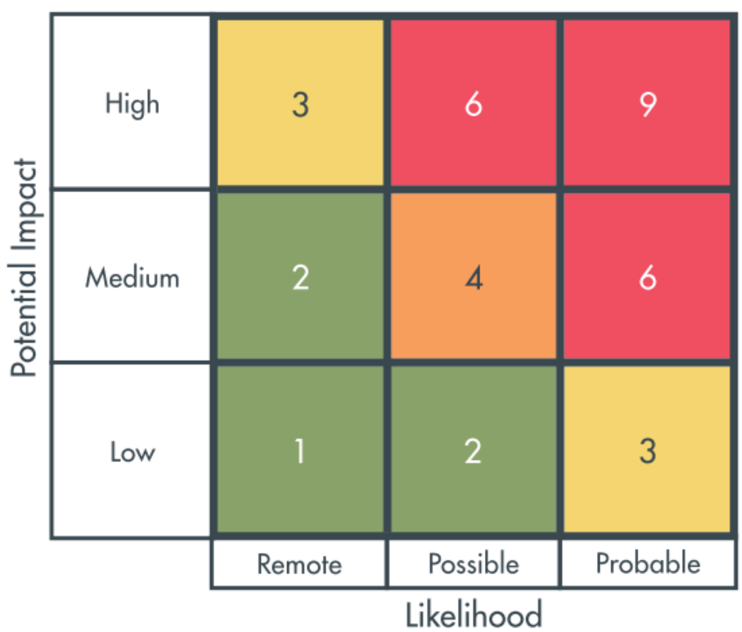


Figure 5. 2. Example of a risk heat map (adopted from CGMA, 2012)

Step 5. Develop ROI heat maps for different farm participation rates: For each value of a chosen varying operation parameter, steps 3 and 4 are repeated to develop the corresponding ROI heat map. The possible increase in ROI would show the economic benefits of improvement in the chosen operation parameter.

Step 6. Quantify the maximum economic benefits: In order to improve the chosen operation parameter, the biorefinery needs to provide economic incentive or captial. However, the magnitude of the economic incentive or capital should not adversely impact the economic performance of the biorefinery. The total potential economic benefits are estimated by comparing the developed heat maps in step 5 (i.e. alternative scenarios) with the one in the base case scenario. The total potential economic benefits show the maximum amount of incentive or capital available to improve the chosen operation parameter.

5.3.2 Evaluation of Incentives

From an investor's perspective, the objective of risk management is to assure that the project can generate a proper return on the invested capital. For this purpose, fundamental key figures such as ROI, Net Present Value (NPV) and Internal Rate of Return (IRR) are used to indicate a project's attractiveness to investors. In this study, the major income and expense components and their variabilities are known, thus, ROI can be applied to compare the profitability of different combinations of income and expense to understand the likelihood of achieving a net gain or a net loss after a fixed period of time. In this chapter, the focus is on the first case where there is a risk associated with the biomass cost and the product market price and the objective is to meet a target annual ROI. In addition, for the scope of this chapter, incentive is defined in a much narrower sense as the payment biomass producers receive excluding nutrient replacement and all of the operation costs of field operations such as biomass harvest and collection (Ma et al., 2012; Golecha & Gan, 2016a; Golecha & Gan, 2016b). In other words, it is the payment biomass producers receive for participation.

Figure 5.3 illustrates the total economic benefits gained by shifting from a base case scenario to an alternative scenario. If the biorefinery shares all of the total economic benefits with biomass suppliers, its final ROI reduces to the same ROI as in the base case scenario. However, if the total incentive provided to the biomass suppliers is lower than the total economic benefits, the expected ROI for the biorefinery increases compared to that of the base case scenario and biomass suppliers also receive some economic incentives.

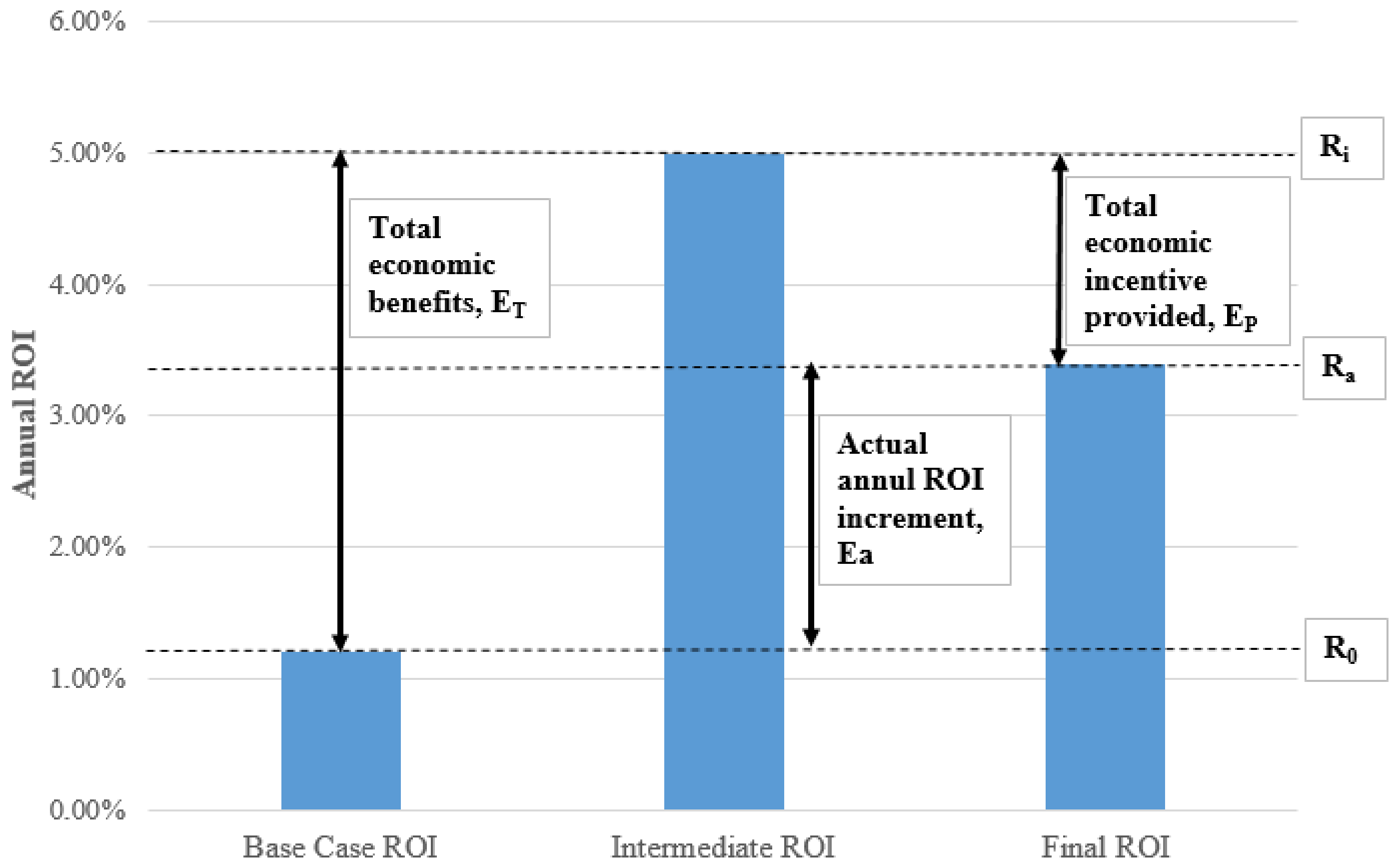


Figure 5. 3. The approach to quantify the maximum economic incentives* available to share with the local biomass producers

**Total economic incentive is an outcome of shifting from a base case scenario to an alternative scenario with a higher farm participation rate. This is the maximum amount of economic benefit can be shared between the biorefinery and biomass suppliers.*

The total economic benefits due to the increased farm participation rate can be estimated as:

$$E_T = C \times (R_i - R_0) \times n \qquad \text{Eq. 5.1}$$

where C is the total capital investment, E_T is the total economic benefit ($), R_0 is the expected annual ROI for the base case scenario, n is the number of years and R_i is the expected annual ROI for the alternative scenario.

The expected annual ROI for the incentive-adjusted scenario can be estimated as:

$$E_a = E_T - E_P \qquad \text{Eq. 5.2}$$

$$R_a = \frac{nCR_0 + E_a}{nC} \qquad \text{Eq. 5.3}$$

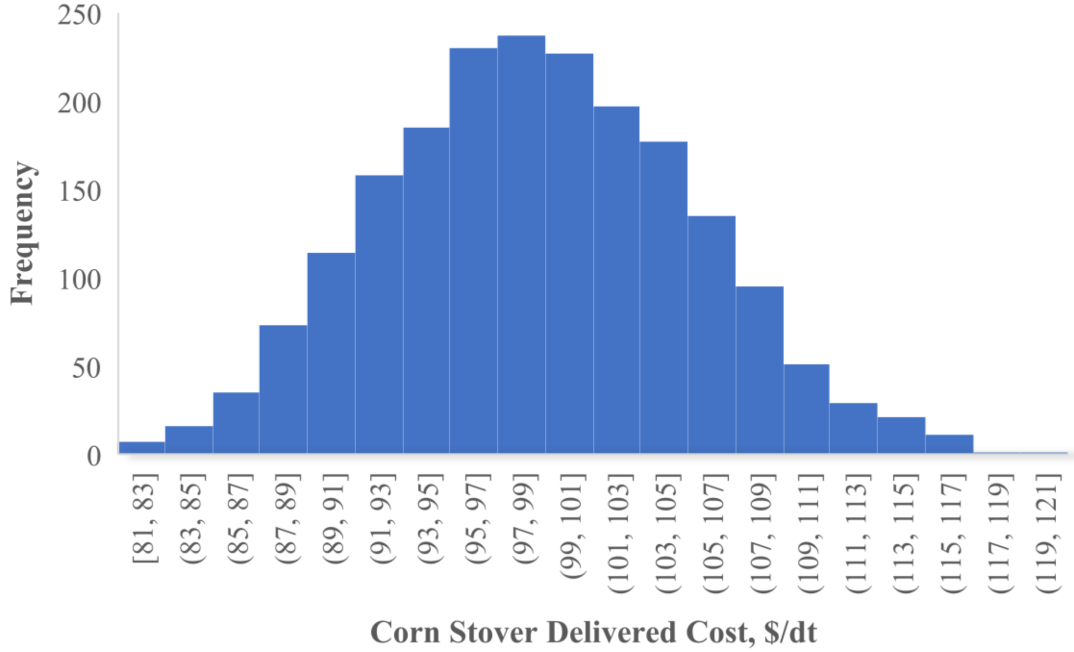
where E_a is the achieved economic benefit ($), E_T is the total economic benefit ($), E_P is the total economic incentive provided ($), R_a is the adjusted expected annual ROI, C is the capital investment ($), n is the number of years and R_0 is the expected annual ROI for the base case scenario.

5.4 Results

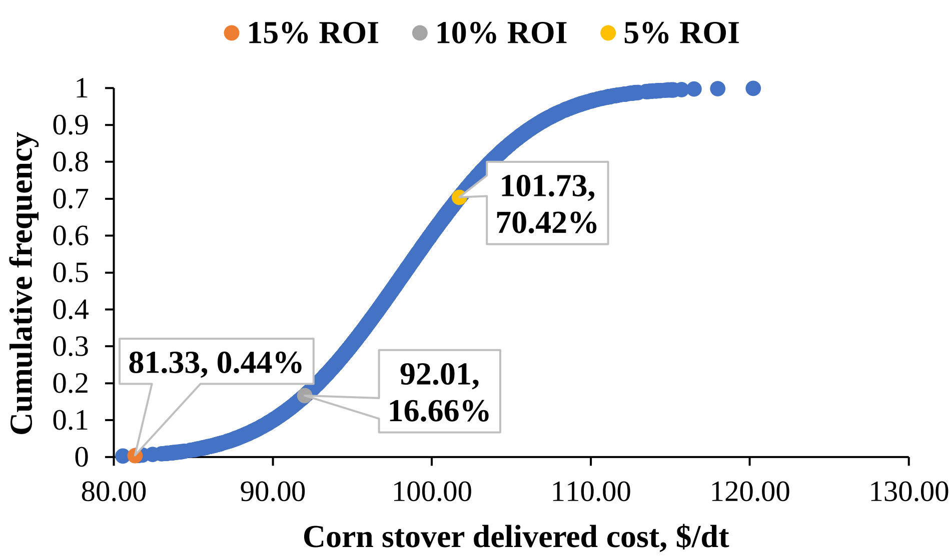
5.4.1 Cost distribution of the biomass delivered cost

IBSAL-MC was applied to determine the different potential values of biomass delivered cost and their probabilities given the variabilities in some of the input parameters including biomass yield, harvest window, harvest moisture content, farm participation rate, bale bulk density, dry matter loss, equipment capacity and efficiency, machine breakdown and repair times, winding factor and road transportation time. To this end, the IBSAL-MC model was run for 2000 replications for the base case scenario. It is estimated that the practical range of farm participation rate would be 20%-50% (Duff & Marchand, 2013; Lauer et al., 2015; Golecha & Gan, 2016[a]; Golecha & Gan, 2016[b]). In this chapter, a conservative value of 20% is assumed for the base case scenario.

Figures 5.4 shows the obtained stover delivered cost distribution and its cumulative distribution function for the base case scenario with 20% farm participation rate. On average, the corn stover delivered cost is estimated to be $98.26/dt with an observed minimum and maximum values of $80.57/dt and $120.21/dt, respectively. In addition, the standard deviation is estimated to be $6.46/dt. Based on the obtained stover cost distribution, the probability of achieving the target biomass delivered cost of $81.33/dt or lower in order to obtain 15% annual ROI in the base case scenario is 0.44%. Thus, it would be very challenging for the biorefinery to meet its economic target with 20% farm participation rate. Based on the average biomass of cost of $98.26/dt and a sugar market price of $400/tonne, the expected ROI is estimated to be 6.8%, less than half of the target value (15.0%). Figure 5.5 shows the observed ranges of cost for all the simulated logistics operations. The highest cost variance is observed in the transportation cost from field-side storage to the intermediate storage. Field operations (windrowing and baling) have the second highest cost variance.



a) Frequency distribution of the corn stover delivered cost



b) Cumulative frequency distribution of corn stover delivered cost*

**The marked points show the delivered costs for 15%, 10% and 5% annual ROI, respectively, and their percentiles. Sugar market price is assumed to be $400/tonne in the base case scenario.*

Figure 5. 4. Base case corn stover delivered cost distribution

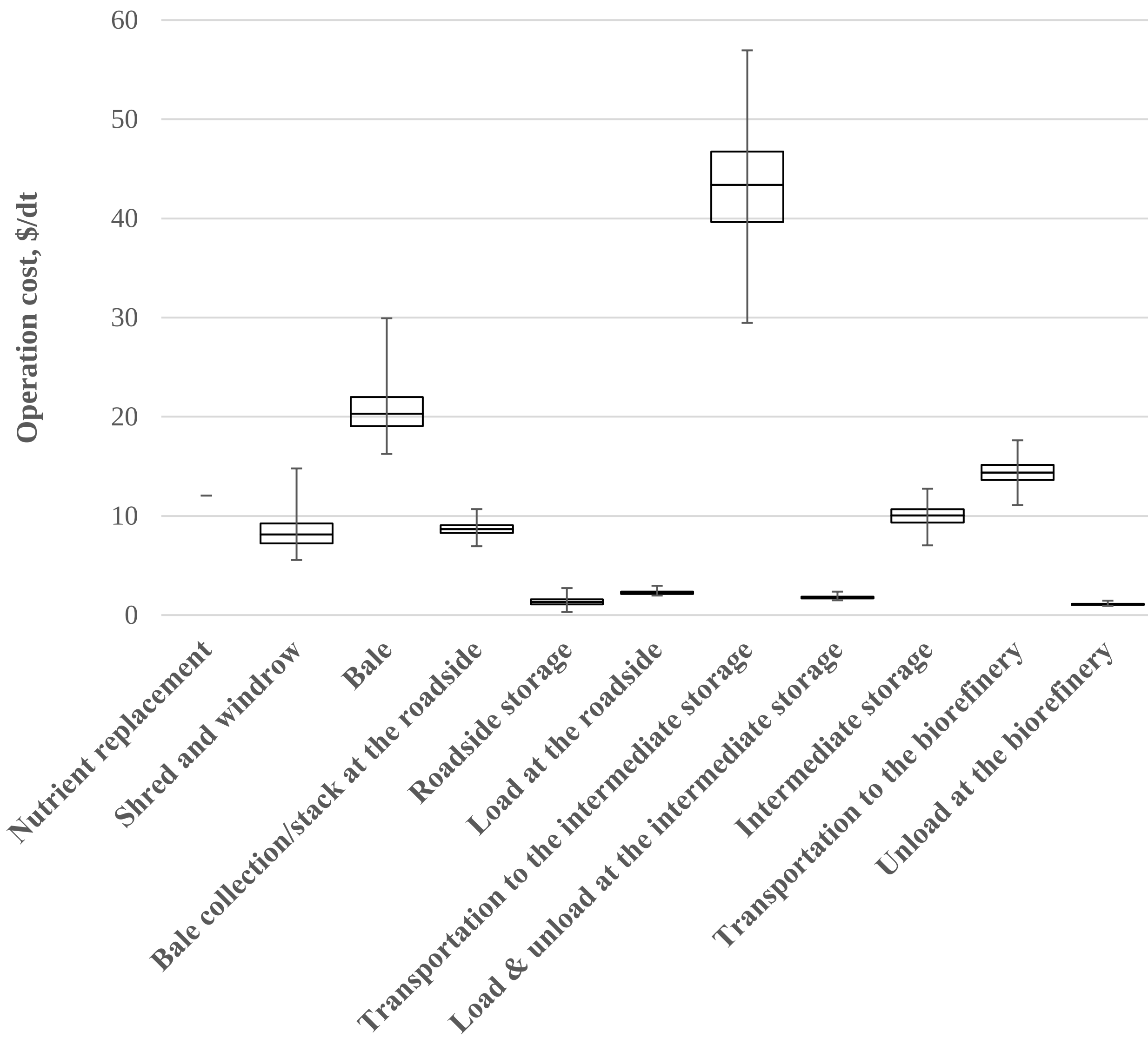


Figure 5. 5. Box-and-whisker chart* of the cost of simulated logistics operations.

**In each box, the three lines from top to bottom indicate the upper quartile, median and the lower quartile, respectively. The observed maximum and minimum values are indicated by the vertical whisker.*

5.4.2 ROI heat map for the base case scenario

Figure 4.6 shows the recent market price distribution of sugar from March, 2012 to March, 2017 based on the historical data provided in Figure 1. During this period, the monthly sugar market price had a mean of $385.55/tonne and a standard deviation of $65.53/tonne.

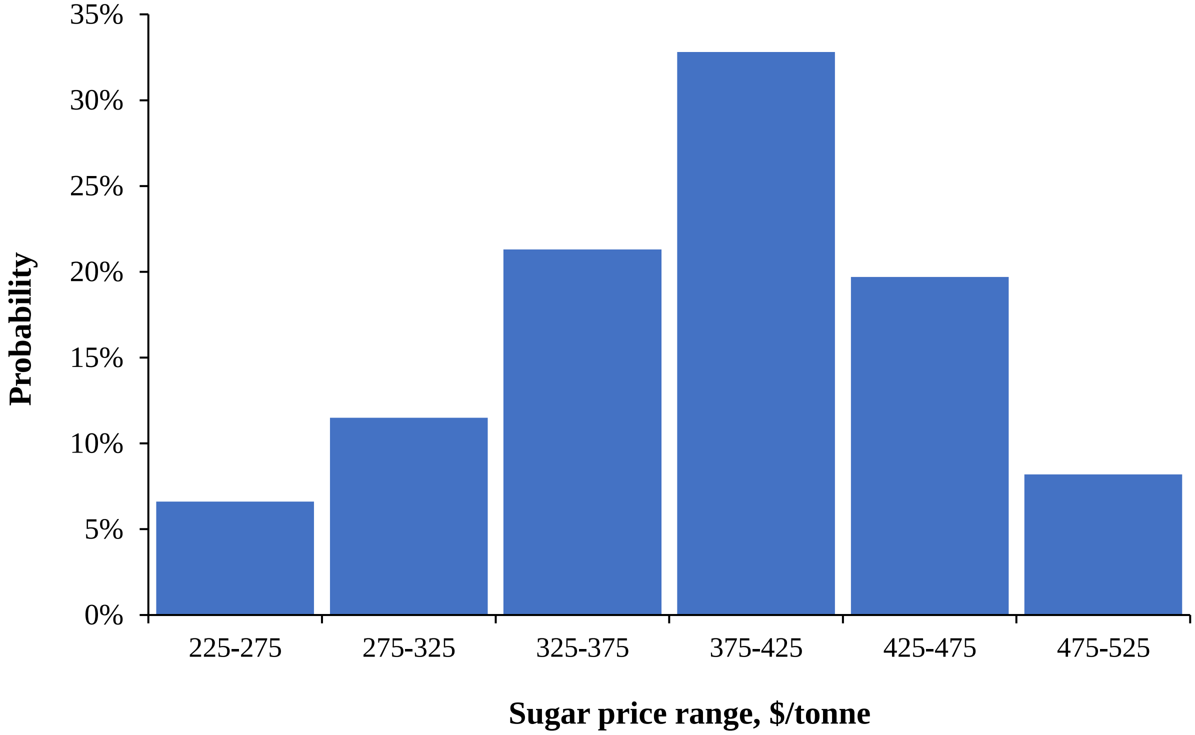


Figure 5. 6. Market price distribution of sugar from March 2012 to March 2017

Given the sugar price distribution in Figure 5.6 and corn stover cost distribution in Figure 5.4, the expected annual ROI can be calculated as follow:

$$R = \sum_{i=1}^{m} P_i R_i \qquad \text{Eq. 5.4}$$

where R is the expected annual ROI, m is the number of combinations, P_i the probability of the occurrence of the ith combination and Ri is the expected annual ROI of the ith combination. A combination refers to a specific pair of sugar price range and stover delivered cost range. Table A3 (appendix) shows the expected ROI for different combinations of sugar price and corn stover delivered cost. Due to the large number of combinations, they are consolidated into larger ranges as shown in Table 5.1. Table 5.1 also shows the probabilities of these consolidated combinations based on the distribution of the corn stover delivered cost in the base case scenario and the sugar market price.

Table 5. 1. Probabilities of the occurrence of the consolidated combination of sugar price and corn stover delivered costs at 20% farm participation rate.

		Sugar market price range, $/tonne					
		225-275	275-325	325-375	375-425	425-475	475-525
Corn stover delivered cost range, $/dt	75-85	0.1%	0.2%	0.4%	0.7%	0.4%	0.2%
	85-95	1.9%	3.3%	6.1%	9.4%	5.6%	2.4%
	95-105	3.6%	6.3%	11.6%	17.9%	10.7%	4.5%
	105-115	0.9%	1.7%	3.1%	4.7%	2.8%	1.2%
	115-125	0.0%	0.1%	0.1%	0.2%	0.1%	0.0%

Table 5. 2. Expected annual ROI for the consolidated combination of sugar price and corn stover delivered costs at 20% farm participation rate

		Sugar market price range, $/tonne					
		225-275	275-325	325-375	375-425	425-475	475-525
Corn stover delivered cost range, $/dt	75-85	-17.9%	-6.7%	4.4%	15.6%	26.8%	38.0%
	85-95	-23.0%	-11.9%	-0.7%	10.5%	21.6%	32.8%
	95-105	-28.2%	-17.0%	-5.8%	5.3%	16.5%	27.7%
	105-115	-33.3%	-22.2%	-11.0%	0.2%	11.4%	22.5%
	115-125	-38.5%	-27.3%	-16.1%	-5.0%	6.2%	17.4%

The expected annual ROI is estimated in Table 5.2 for each combination in Table 5.1. The ROI heat map can be developed by combining the probabilities in Table 5.1 and the ROIs in Table 5.2. Figure 5.7 shows the ROI heat map for the base case scenario. The expected annual ROI for the base case scenario with a 20% farm participation rate is estimated to be 1.3% given stover costs, sugar prices and their probabilities.

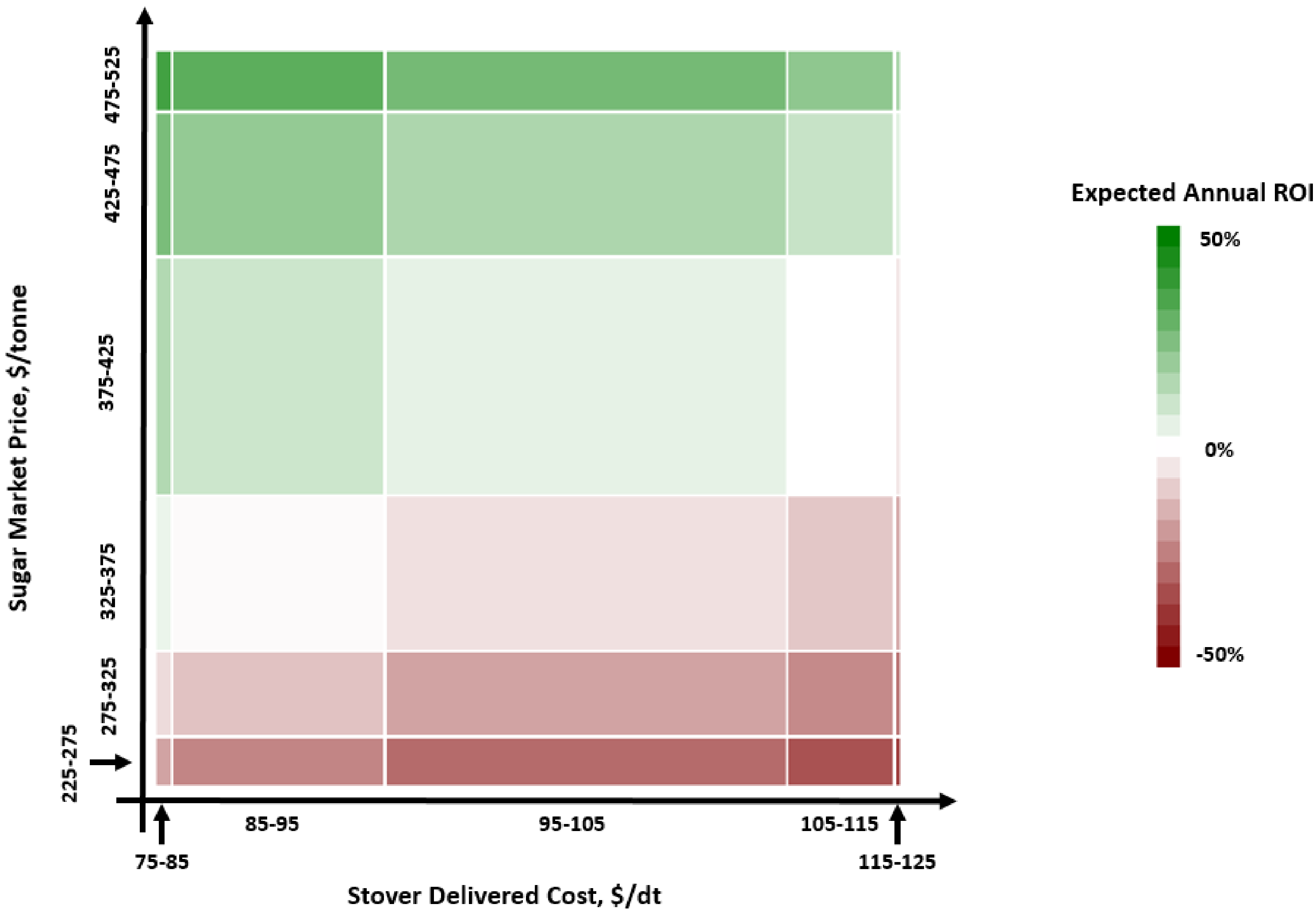
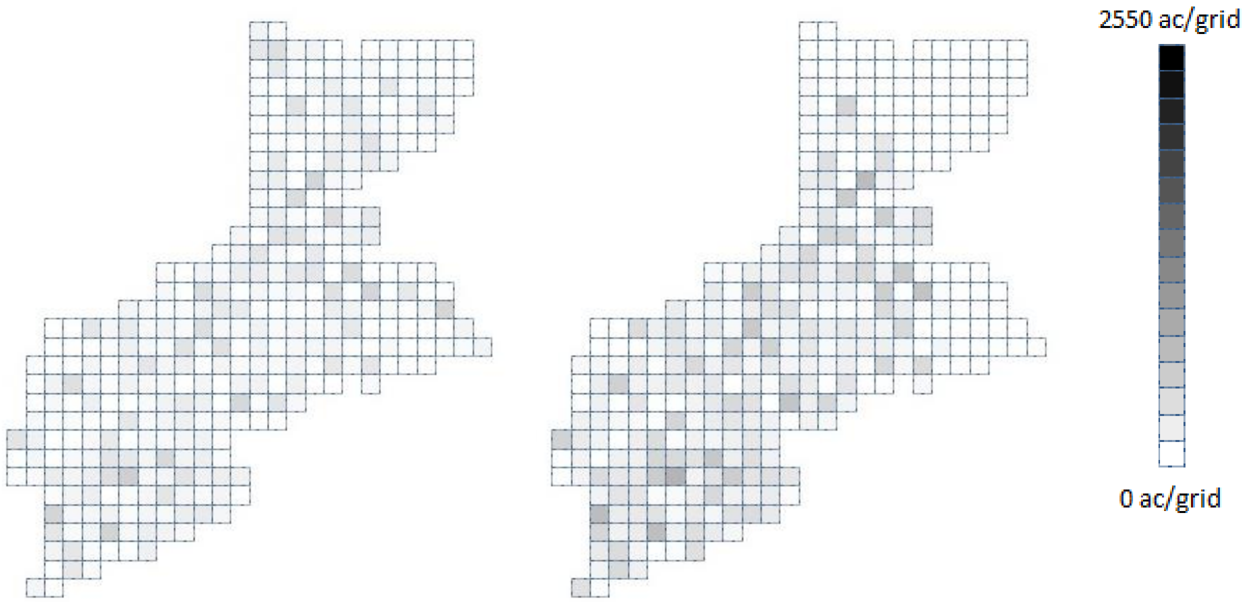


Figure 5. 7. ROI heat map* for the base case scenario.

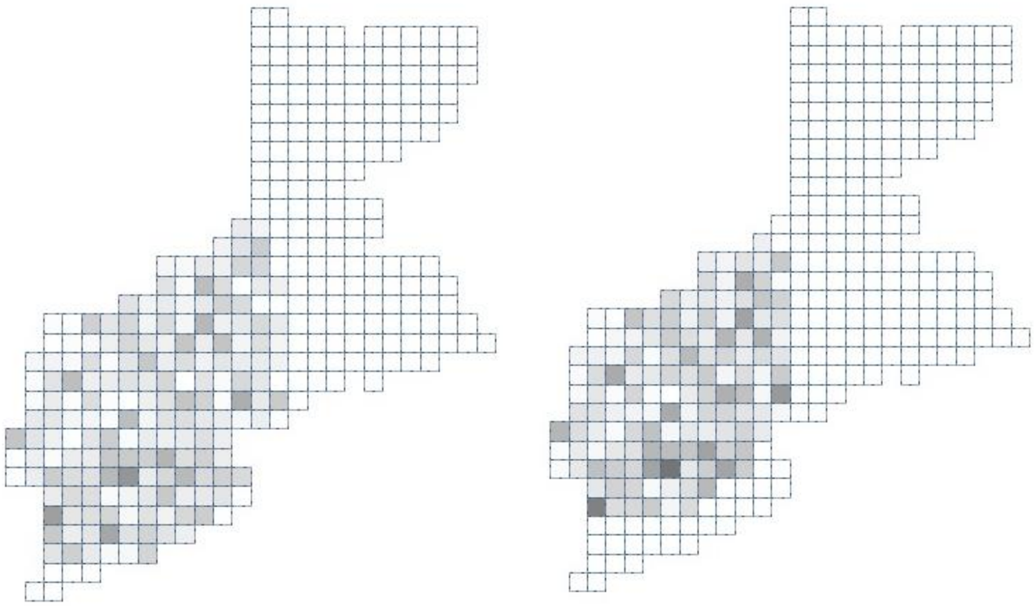
**Each rectangle represents a combination of sugar market price range and corn stover delivered cost range. The length of a rectangle indicates the probability of the occurrence of the respective corn stover delivered cost range. The width of a rectangle indicates the probability of the occurrence of the respective sugar market price range. Therefore, the area of the rectangle indicates the probability of the occurrence of the respective combination. Finally, the color of a rectangle indicates the range of expected annual ROIs for the respective combination. The expected annual ROIs of the most top left and bottom right rectangles are estimated to be 38.0% and -38.5%, respectively.*

5.4.3 Develop heat maps for different farm participation rate scenarios

In the previous section, an ROI heat map was developed for the base case scenario with a 20% farm participation rate. As shown in Figure 5.8, with the increase in the farm participation rate (e.g. from 20% to 30%, 40% and 50%), the size of the required supply area and the supply radius decreases. This leads to the reduction in transportation distances and the amount of time logistic machines need to travel among corn fields. Therefore, as farm participation rate increases, a decrease in the corn stover delivered cost is expected.



a) 20% farm participation rate b) 30% farm participation rate



c) 40% farm participation rate d) 50% farm participation rate

Figure 5. 8. Corn stover supply area for different farm participation rate scenarios*

**For 20%, 30%, 40% and 50% farm participation rate scenarios, the estimated supply radius from the location of the biorefinery in Sarnia is estimated to be 120km, 100km, 66km and 60km, respectively.*

The stover delivered cost distributions for 20% (base case), 30%, 40% and 50% farm participation rates are shown in Figure 5.9. As expected, a decrease in the corn stover delivered cost is observed as farm participation rate increases. The average stover delivered cost is estimated to be $93.85/dt, $91.23/dt and $90.24/dt, with a standard deviation of $5.62/dt, $5.39/dt and $5.41/dt in 30%, 40% and 50% farm participation rates, respectively, whereas the average corn stover delivered cost was estimated to be $98.26/dt with a standard deviation of $6.46/dt in 20% farm participation rate. Due to the non-circular shape of the supply area, the non-centric location of the biorefinery and the non-uniform distribution of the corn fields, the changes in the average and standard deviation of the biomass delivered costs from 20% participation rate to 50% rate is not linear.

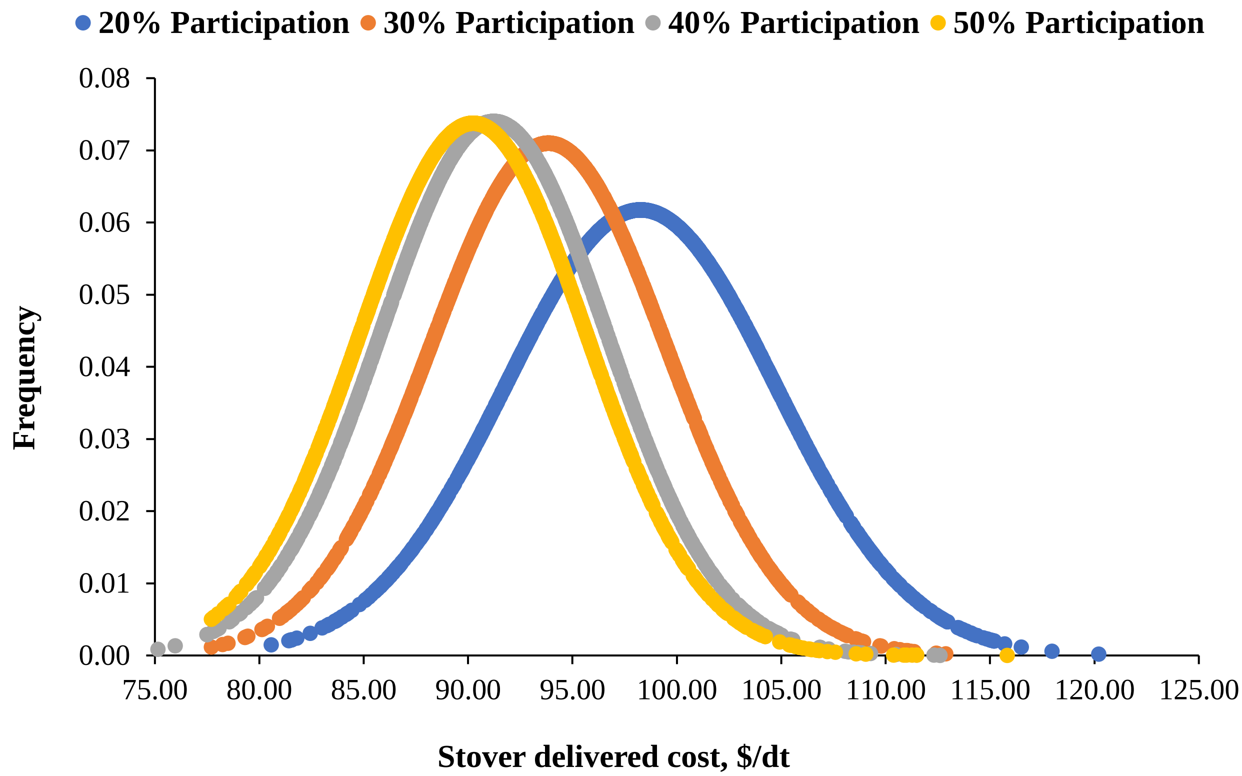


Figure 5. 9. Corn stover delivered cost distribution for 20%, 30%, 40% and 50% farm participation rates

As the corn stover delivered cost distribution shifts to the left in Figure 5.9 with increasing farm participation rate, the probability of combinations of sugar market price and stover cost shown in Table 5.1 would change. Tables A8, A9 and A10 show these probabilities for 30%, 40% and 50% farm participation rates, respectively. Figure 5.10 shows the ROI heat maps for 20%, 30%, 40% and 50% farm participation rates. The expected annual ROI for 30%, 40% and 50% participation rates are estimated to be 3.4%, 4.6% and 5.1%, respectively. In all three cases, the expected annual ROI is higher than that of the base case scenario (1.3%) due to the reduction in stover delivered cost.

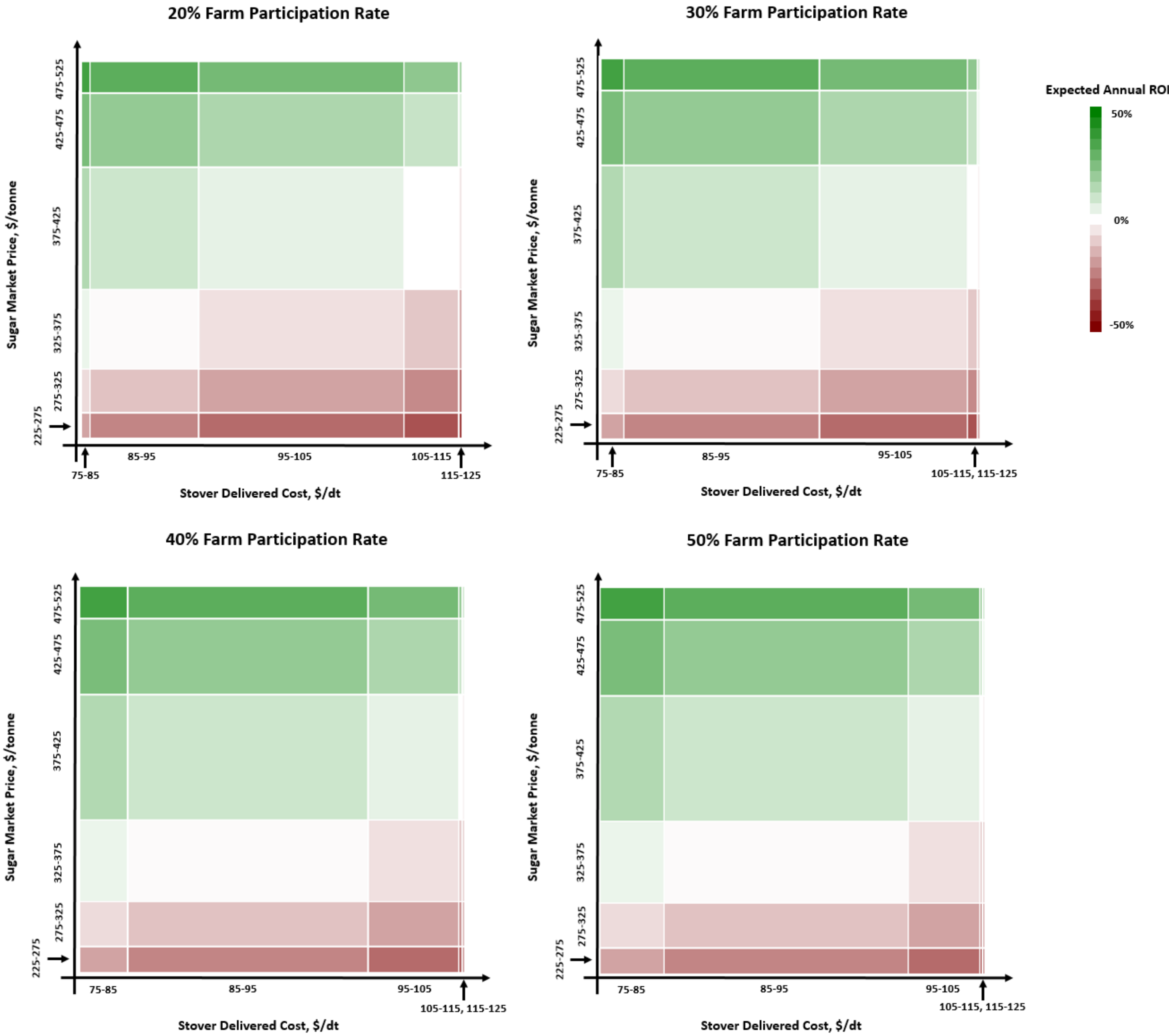


Figure 5. 10. ROI heat maps* for 20%, 30%, 40% and 50% farm participation rate scenarios

**For each of the heat map, the expected annual ROIs of the most top left and bottom right rectangles are estimated to be 38.0% and -38.5%, respectively.*

As shown in Figure 5.10, when farm participation rate increases (from 20% to 30%, 40% and 50%), there is no impact on the sugar market price and the sugar market price distribution does not vary on the vertical axis, because it is assumed that the local biomass yield and sugar production capacity cannot influence the global sugar market price. On the other hand, the corn stover delivered cost distribution on the horizontal axis shifts with the change in the farm participation rate. The corn stover delivered cost is more likely to be in the lower range ($75-85/dt and $85-95/dt) with the increase in the farm participation rate. Therefore, the combination of sugar market price and corn stover delivered cost is more likely to achieve a higher expected annual ROI (indicated by the increasing size of the green rectangles). It is observed that while increasing farm participation rate is economically beneficial to the biorefinery, there are more economic benefits if the sugar market price is in the favourable range (e.g. $375+/tonne).

5.4.4 Quantify the maximum economic incentives for biomass producers

Given the expected annual ROI for each farm participation rate in Figure 5.10, the potential economic benefits can be estimated by comparing the expected annual ROI between the base case scenario and the alternative ones. Table 5.3 shows that as the farm participation rate increases, the total economic benefit would increase from $2,276,000 (Case 1) to $3,636,000 (Case 2) and $4,138,000 (Case 3). Thus, the maximum amount of available incentive for the biorefinery to offer to corn growers increases by 60% and 82% from Case 1 to Case 2 and Case 3, respectively.

Table 5. 3. Economic benefits as an outcome of increase in farm participation rate

Increase in farm participation rate	10-year economic benefits ($)
Case 1: from 20% to 30%	2,276,000
Case 2: from 20% to 40%	3,636,000
Case 3: from 20% to 50%	4,138,000

The economic incentive can be provided to biomass suppliers in different forms, such as $/dt or $/acre. Figure 5.11 shows the expected incentive-adjusted annual ROI for different amounts of incentive provided to biomass suppliers in the form of $/dt for different farm participation rates. Without providing any incentive, the expected annual ROI was estimated to be 3.4%, 4.6% and 5.1% for 30%, 40% and 50% farm participation rate, respectively. As the incentive increases, the expected incentive-adjusted annual ROI declines. In the case of shifting from 20% to 30% participation rate, the breakeven point takes place at $2.88/dt meaning that by paying $2.88/dt to corn growers, the biorefinery would expect the same ROI as in the base case scenario (1.3%). Thus, $2.88/dt is the maximum incentive that can be provided to the corn growers to increase farm participation rate from 20% to 30%. The breakeven points for 40% and 50% cases occur at $4.61/dt and $5.11/dt, respectively. As shown in Figure 5.11, there is more than one strategy to achieve a target annual ROI. For instance, if the target annual ROI is over 3%, it can be achieved by either offering an incentive of $1.27/dt to achieve 40% farm participation rate or offering an incentive of $2.53/dt to achieve 50% farm participation rate. The right strategy requires a deep understanding of factors influencing biomass suppliers' willingness to participate in the supply area beyond economic incentives provided by the biorefinery. It is not within the scope of this chapter to identify the influential factors and determine the best strategy.

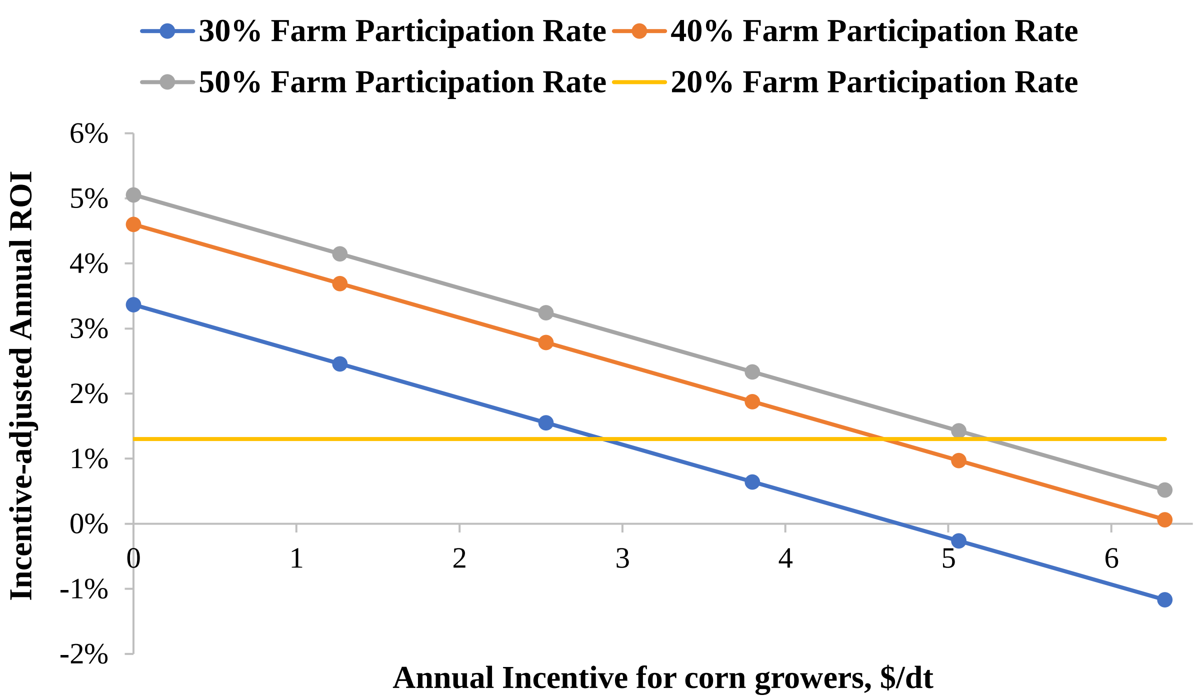


Figure 5. 11. Expected final annual ROI vs. additional farmers' incentive per dry tonne of corn stover at 30%, 40% and 50% farm participation rate.

The breakeven points of the incentives are relatively low due to the negative economic impact of the probability of low sugar market price. When the sugar market price is at

$375+/tonne (instead of $275+/tonne), the expected annual ROI would increase to 9.5%, 11.4%, 12.6% and 13.0% in 20%, 30%, 40% and 50% farm participation rates, respectively. Consequently, the breakeven points of the incentives would increase to $14.10/dt, $15.77/dt and $16.33/dt. This implies that the increase in the price of the sugar can increase in the farm participating rate.

The results show that higher economic incentives can be shared with corn growers as farm participation rate increases. A high participation rate in the biomass supply systems of existing and emerging biorefineries is imperative in short run to secure the sufficient supply of biomass to their biorefineries. If the supply of biomass increases in long run, a biorefinery may still need to compete with other end users to encourage biomass producers to participate in its supply system. More research is needed to determine the long-term impact of the development of regional biomass markets on biomass production, utilization and trading price as various bio-conversion technologies and bio-product markets are emerging.

This chapter focuses on corn stover (crop residues) that is already being produced by corn growers and is usually left in the field. The main concern in this chapter is the participation of corn growers to supply their corn stover to a biorefinery, rather than providing incentives for corn growers to allocate more land toward continuous corn production. A different incentive program needs to be developed if the main concern is to secure sufficient acreage of biomass production, for example, production of dedicated biomass crops such as switchgrass and miscanthus in agricultural lands that are less suitable for growing conventional row crops. In that case, the developed methodology in this study can be adopted to quantify incentives for increasing the production of biomass.

In this chapter, it is assumed that the biorefinery contracts with the individual biomass producers. However, the year-to-year variation in biomass supply may affect the level of biomass producers' willingness to participate in short and long-term contracts. One approach to reduce the uncertainties on the supply side is to adopt an alternative supply governance structure, under which a farmers' co-operative is formed. In such a supply governance, the cooperation can receive economic benefits from owning shares of the biorefinery in addition to receiving incomes from supplying biomass to the biorefinery. It can also potentially lead to reduced administrative and logistics management costs, shared economic risk and benefits and improved competitiveness of the final products.

This chapter focused on quantifying the impact of the farm participation rate on the biomass delivered cost. The developed methodology can be adopted for other input parameters such as the price of the co-product(s), the biomass-to-final product conversion cost and yield and the biomass yield to evaluate their combined impacts on the economic performance of a biorefinery.

5.5 Discussion

The economic performance of a biorefinery does not only depend on the biomass supply cost. The price volatility of the final products also poses economic risk to the economic sustainability of the biorefinery. In this chapter, a developed approach is presented to quantify the combined impact of the variability in the biomass delivered cost and the product market price on the expected ROI of a biorefinery. In addition, the potential economic incentives for biomass producers are quantified by changing the farm participation rate. The Monte Carlo simulation model, IBSAL-MC, is used to estimate the biomass delivered cost distribution and the risk heat map is used to evaluate the economic performance of the biorefinery and to quantify economic incentives for biomass producers. The results show the effectiveness of the developed model both to evaluate the economic performance of the biorefinery and to quantify the potential economic incentives for the biomass suppliers.

The results also show that as the farm participation rate increases, the corn stover delivered cost distribution shifts towards a lower range of costs primarily due to the decrease in the size of the supply area. The reduction in the biomass delivered cost would result in the increase in the expected ROI. A portion of this economic benefit can be shared with biomass producers to increase their willingness to participate in the biomass supply system. In addition, the increase in the price of the final product could lead to the increase in the expected ROI, and thus, more potential incentive for biomass suppliers to participate.

5.6 Conclusion

In this chapter, it is assumed that the biorefinery contracts with the individual biomass producers - a firm-farm (FF) supply chain governance structure. An alternative supply governance structure is to form a farm co-operative among participating farmers – a firm-co-operative-farm (FCF) supply chain governance structure. On the one hand, the co-operative has the negotiation power to obtain more economically rewarding contracts from the biorefinery. On the other hand, it significantly reduces the amount of administrative work and biomass harvest work the biorefinery needs to complete.

Under the FCF supply chain governance structure, because of the capital it holds, the co-operative can also receive economic benefits from owning shares of the biorefinery in addition to receiving incomes from supplying biomass to the biorefinery. In this case, it does not only potentially lead to reduced administrative and logistics management costs, but also forms a reciprocal partnership between the biorefinery and the farmers' co-operative to share economic risk and benefits, thus, potentially provides additional motivation for the biorefinery and members of the co-operative to work together to improve the level of competitiveness of the final products. In the next chapter, the FCF supply governance structure will be analyzed to evaluate its economical feasibility.

Chapter 6. Opportunities for Farmers' Co-operative

6.1 Synopsis

In the last chapter, a quantified approach has been developed to perform supply and demand economic performance and risk analysis for an industrial scale biomass project. It shows that farm's participation rate can be critical to the long term economic success and sustainability of a biomass project. In addition, the potential amount of economic incentives for biomass producers have been quantified under the FF supply chain governance structure. This chapter aims to explore the potential of the FCF supply chain governance structure, thus, a sample farmers' co-operative (based on communication with the CSPC) is introduced to quantify the economic benefits it can provide to the biorefinery and participating biomass producers. Furthermore, a sensitivity analysis is conducted on a number of characteristic parameters of the farmers' co-operative to seek a reciprocal business structure for the biorefinery, the farmers' co-operative and participating biomass producers.

6.2 Objectives and Contributions

In the previous chapters, only the FF supply chain governance structure has been considered. Under this structure, both biorefinery and biomass suppliers face considerable financial risk due to variability in biomass supply operation costs and market price of the product. Although through long term partnership and contract, the financial risk can be eased, not all farm owners are willing to share the costs, schedules and standards with the biorefinery (Curtis, 2013; Niu et al., 2016). One possible alternative is the FCF supply chain governance structure. Under this structure, the co-operative ideally acts on behalf of all the member farm owners to protect their benefits with its larger bargaining power and reduced administrative costs (Wang et al., 2014; Niu et al., 2016).

Upon literature review, there exists a rich body of knowledge on the social dynamics, organization structure and operation and increment in bargaining power and market share of co-operatives in established markets. However, there is lack of quantitative studies on the economic benefits co-operative can create for both members and the biorefinery in a local biomass market that does not exist previously. Furthermore, it is also rarely discussed when the co-operative owns shares of the upstream processing firm. In this chapter, a simple farmers' co-operative is introduced to manage the corn stover supply (63,000 dt/year) to a cellulosic sugar production facility located in Southwestern Ontario, Canada based on information obtained during communication with the CSPC. The farmers' co-operative also invests approximately 40% of the biorefinery's total capital cost, and the earnings it received from the biorefinery's operation will be distributed among its members. Return on Investment (ROI) is used as the basis to quantity the economic benefits to co-operative members and biorefinery investors while variability in supply system operation costs and sugar market price are both considered. The obtained results are visualized through risk heat maps to facilitate the communication between co-operative members and investors to develop a sustainable reciprocal long-term partnership and risk mitigation strategy.

6.3 Methodology

In this chapter, the Monte Carlo simulation and the economic performance and risk analysis developed in Chapter 4 and 5 were applied to evaluate the base case scenario, in which a simple farmers' co-operative was introduced to form a FCF supply chain governance structure. In the farmers' co-operative base case scenario, the farmers' co-operative contracts 46,000 acres of corn field within 90 km distance to the biorefinery. For the 63,000 dt annual biomass demand of the biorefinery, it will pay $30/dt to members of the farmers' co-operative and a portion (based on the percentage of ownership of the biorefinery) of the net profit from selling the produced sugar. The farmers' co-operative also collects a one-time membership fee ($500 plus $200/acre) from participating corn field owners. Since the farmers' co-operative needs to contract 46,000 acres of corn field, the total amount of membership fee collected is at least $9,200,000, which is approximately 40% of the biorefinery's total capital cost. Figure 6.1 summarizes the business relationship described above between the farm owners, the farmers' co-operative and the biorefinery.

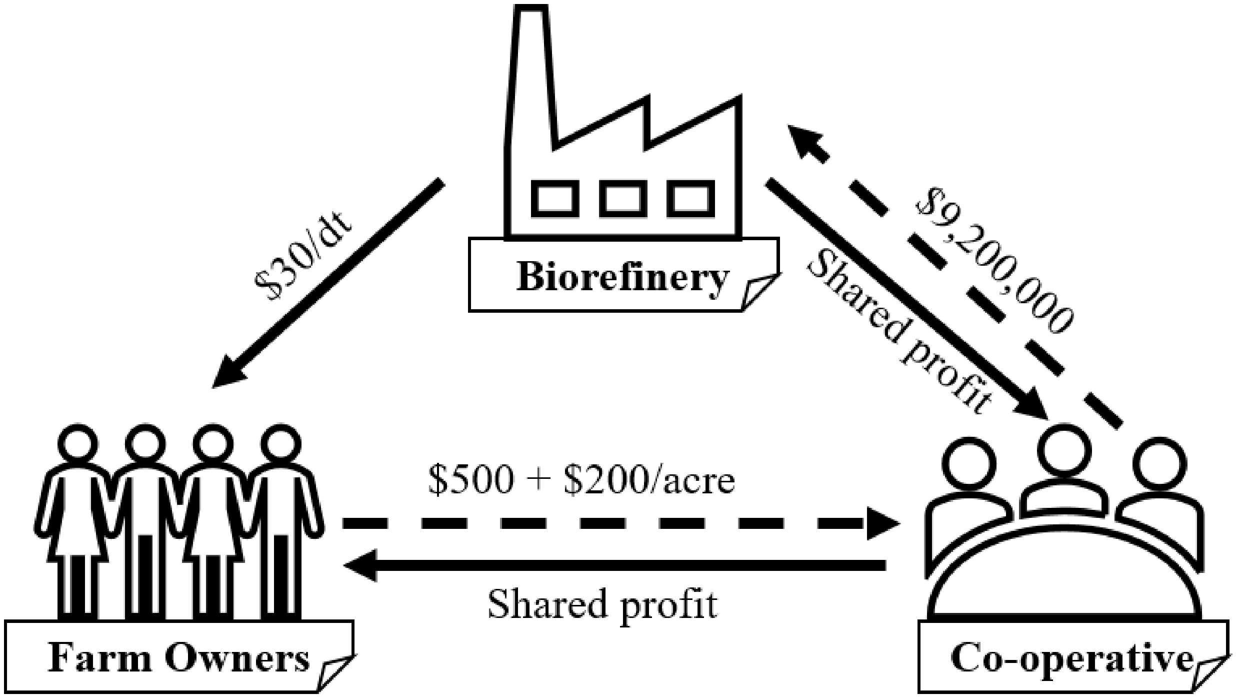


Figure 6. 1. Structure* of business relationship between farm owners, co-operative and biorefinery

**The dashed lines indicate two one-time payments, a membership fee farm owners pay the co-operative and a capital the co-operative invests into the biorefinery. The solid lines indicate three annual transactions, the $30/dt of corn stover the biorefinery pays to the farm owners, the profit the biorefinery shares with the co-operative based on the percentage of the co-operative's share and the profit the co-operative shares with farm owners based on their percentage of participated corn fields. At the end of the project, the co-operative aims to achieve net zero, thus, all the profit received from the biorefinery will be distributed among its members.*

Based on the typical farm size of the supply area, three corn field sizes, 100, 500 and 1,000 acres, are chosen to analyze the economic benefits for individual members of the farmers' co-operative assuming at the end of the biomass project's 10-year lifetime, the farmers' co-operative achieves net neutral (all the profits are distributed among its members).

Sensitivity analysis was performed on two parameters involved in the business structure and operation of the farmers' co-operative, including an alternative distribution of the biomass purchase payment, a guaranteed return of the farmers' co-operative's investment over 10 years and reducing maximum supply distance. The results from the economic performance and risk analysis were compared with the base case scenario in order to gain insights of which parameters could be beneficial to the long-term economic sustainability of the farmers' co-operative while at the end of the project, the farmers' co-operative achieves a profit of net zero and the biorefinery and members of the farmers' co-operative both achieve a reasonable annual ROI.

6.4 Results

6.4.1 Farmers' Co-operative Base Case Scenario

Table 3.2, 6.1 and 6.2 summarize the economic parameters of the biorefinery and the logistic equipment involved. Out of the \$10,675,000, it is assumed that the farmers' co-operative invests for the cornstalk shredders, square balers and bale collectors/stacks. The tractors are assumed to be available from members of the farmers' co-operative due to the existing agricultural activity in the area. The trailer trucks for transportation from roadside storage to the intermediate storage are contracted during the harvest season, thus, they do not require a capital cost. The trailer trucks for transportation from the intermediate storage to the bio-refiner and the telescopic bale loaders belong to the biorefinery, thus, it is not part of the capital investment from the farmers' co-operative. As a result, the farmers' co-operative invested \$5,135,000 to establish the logistics fleet to meet the biorefinery's annual biomass demand. The logistics equipment investment increases the total capital cost required for the biorefinery and a dedicated logistics fleet to \$22,775,000, thus, the membership fee collected by the farmers' co-operative accounts for approximately 40% of the total capital cost.

Table 6. 1. Economic parameters* for the cellulosic sugar production project in Sarnia

Capital Investment	
Plant Capacity (tonne/year)-Corn stover	63,000
Capital Cost ($)	17,640,000
Logistics Equipment Cost ($)	10,675,000
Loan ($)	8,820,000
Production and Revenue	
Total Revenue ($/year)	12,499,200
Feedstock cost ($/year)	5,123,790
Production cost ($/year)	2,520,000
Financing cost	
Loan payment including interest	1,142,230

**All monetary values are in Canadian dollars. The capital cost does not include the investment required to establish a dedicated harvesting and transportation fleet % (Duffy & Marchand, 2013; Marchand, 2015).*

Table 6. 2. Logistics equipment required for the base case scenario

Equipment	Number of machine	Economic Value ($)
Cornstalk shredder	13	455,000
Square baler	12	1,680,000
Bale collector/stacker	12	3,000,000
Tractor (185-220 hp)	25	5,000,000
Telescopic bale loader-roadside of corn fields	5	450,000
53-ft flatbed trailer truck-roadside of corn fields	13	-
Telescopic bale loader-intermediate storage site	5	-
53-ft flatbed trailer truck-intermediate storage site	3	-
Telescopic bale loader-cellulosic sugar facility	1	90,000
Total	84	10,675,000

The logistics cost distribution for supplying 63,000 dt corn stover within 90 km distance to the biorefinery is summarized in Table 6.3. The participating farmers pay for the nutrient replacement cost, the farmers' co-operative is responsible for the logistics costs prior to storage, including windrow, baling, in-field transportation, field-side storage, field-side load and transportation from field-side to the intermediate storage operated by the biorefinery, and the biorefinery is responsible for the remaining logistics costs, including unload/load at intermediate storage, intermediate storage, transportation from the intermediate storage to the biorefinery and unload at the biorefinery. The standard deviation of the biorefinery's logistics cost is smaller than that of the farmers' co-operative's, because the transportation distance between the intermediate storage and the biorefinery is fixed.

Table 6. 3. The logistics costs of 63,000 dt corn stover within 90 km distance to the biorefinery

	Parties involved in the supply chain		
	Farmers	Farmers' Co-operative	Biorefinery
Maximum logistics costs, \$/dt	12.05	70.42	25.79
Average logistics costs, \$/dt	12.05	59.30	20.90
Minimum logistics costs, \$/dt	12.05	51.72	16.86
Standard deviation, \$/dt	0.00	2.92	1.42

At a sugar price of \$400/tonne and a delivered corn stover cost of \$50.90/dt (\$30/dt paid to members of farmers' co-operative and \$20.90/dt of biorefinery's logistics cost), the biomass project can achieve an annual ROI of 6.9%. The farmers' co-operative's \$9,200,000 investment represents 40% of the biorefinery's total capital cost, but it owns approximately 66% share of the biomass project (\$13,955,000 excluding \$8,820,000 of loan). A result, 66% of the net profit from the sales of the produced sugar counts as revenue for the farmers' co-operative. However, the \$2,845,000 payout (66% of \$43,155,000) the farmers' co-operative receives each year is not enough to cover the \$4,252,000 average annual logistic costs of corn stover harvesting and transportation. Figure 6.2 is the ROI heat map for the farmers' co-operative when fluctuation in the logistics and the sugar market price are both considered, and the expected annual ROI is -16.5%. Since this outcome is not economically sustainable for the farmers' co-operative, the economic return for its members cannot be evaluated. At the same time, the expected annual ROI for other investors of the biomass project is 6.7%. This shows that the base case scenario poses high risk to the farmers' co-operative's financial well being. The economic benefits and risks are not balanced between members of the farmers' co-operative and other investors of the biomass project.

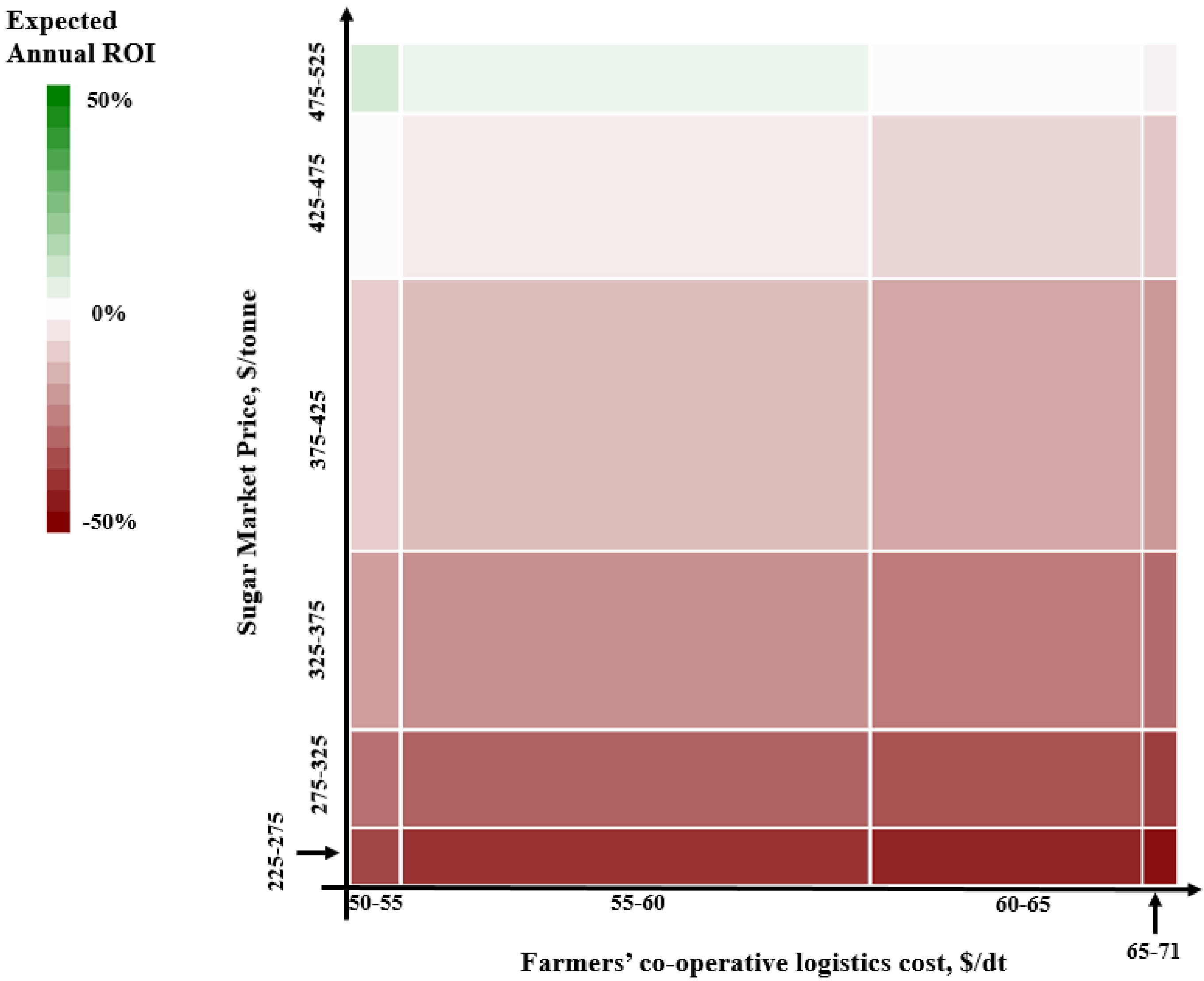


Figure 6. 2. ROI heat map for the base case farmers' co-operative

Figure 6.2 also shows that the expected annual ROI for the farmers' co-operative is only positive (2.6%) when the sugar market price is in the highest range, $475-525/tonne, and the farmers' co-operative's logistics cost is in the range of $50-65/dt. The probability of this scenario is 7.9% based on the sugar market price distribution shown in Figure 5.6 and the farmers' co-operative's logistics cost distribution shown in Table 6.3. Furthermore, if the biorefinery can maintain the product's selling price within the range of $475-525/tonne, the expected annual ROI for the farmers' co-operative is 3.6%. When this is achieved, the expected annual ROI for other investors of the biomass project is 16.2% and the expected annual ROI for three hypothetical members of the farmers' co-operative are listed in Table 6.4.

Table 6. 4. Expected annual ROI for participating members under base case scenario when sugar price is in the range of $475-525/tonne

Farm	A	B	C
Acre	100	500	1000
Membership fee, $	20,500	100,500	200,500
Gross profit, $	50,000	249,500	499,000
Expected annual ROI	14.3%	14.8%	14.9%

6.4.2 Sensitivity Analysis

Sensitivity analysis is performed on two parameters involved in the business structure and operation of the farmers' co-operative, including an alternative distribution of the biomass purchase payment, a guaranteed return of the farmers' co-operative's investment over 10 years and reducing maximum supply distance. A profitable scenario is achieved by altering the three considered parameters in favour of the farmers' co-operative from the base case scenario.

In the alternative biomass purchase payment scenario, the $30/dt payment from the biorefinery is distributed among participating farmers ($25/dt) and the farmers' co-operative ($5/dt). Under this payment structure, participating still receives enough to cover the nutrition replacement cost ($12.05/dt), thus, resulting in an economic incentive of $12.95/dt for participating. Figure 6.3 shows the farmers' co-operative's ROI heat map with an expected annual ROI of -13.1%, whereas in the base case, the expected annual ROI is -16.5%. The probability of achieving a positive annual ROI is 9.4% based on the sugar market price distribution shown in Figure 5.6 and the farmers' co-operative's logistics cost distribution shown in Table 6.3. If the biorefinery can maintain the product's selling price within the range of $475-525/tonne, the expected annual ROI for the farmers' co-operative increases to 7% from 3.6% in the base case. When this is achieved, the expected annual ROI for other investors of the biomass project is 16.2% and the expected annual ROI for three hypothetical members of the farmers' co-operative are listed in Table 6.5.

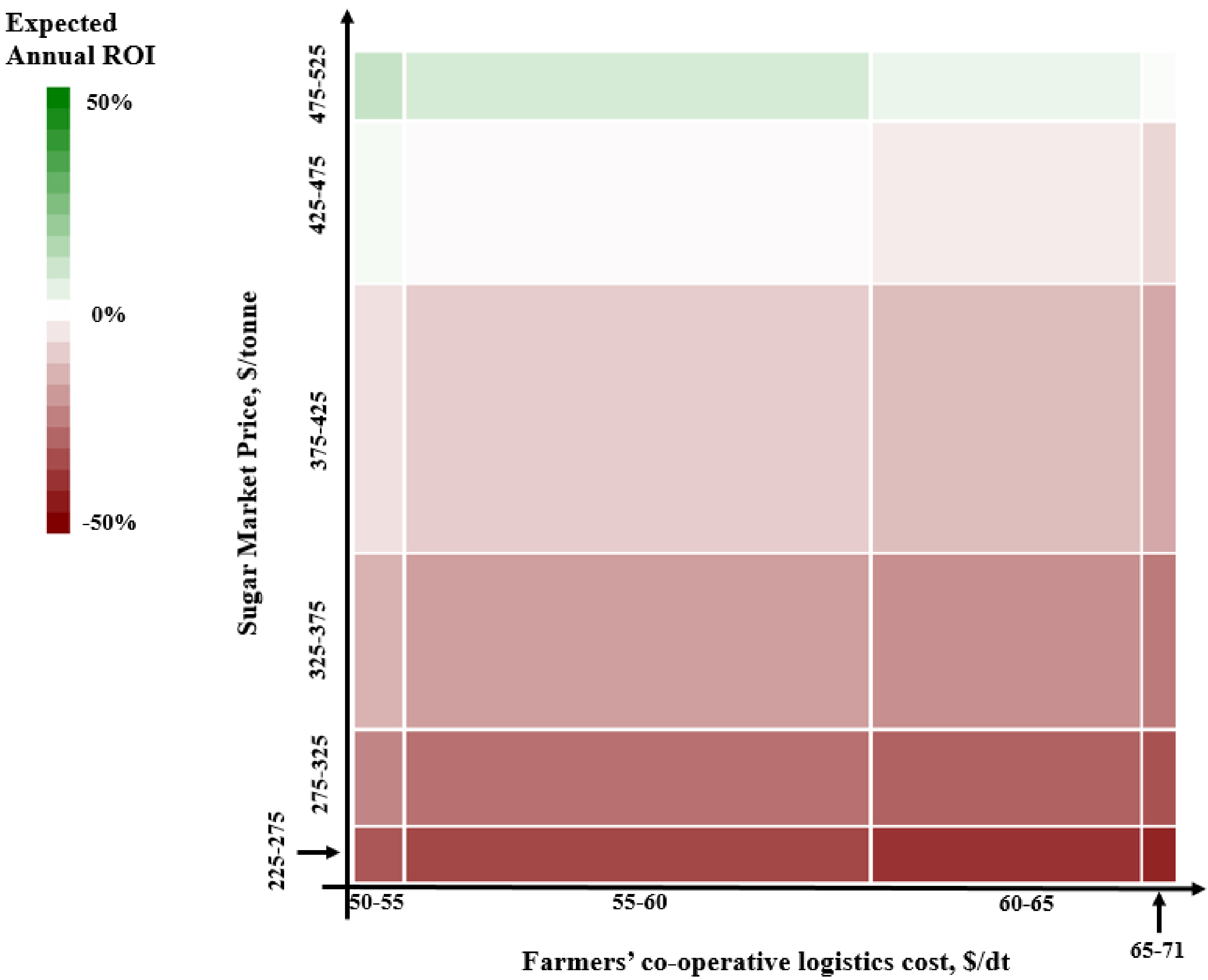


Figure 6. 3. ROI heat map for farmers' co-operative under the alternative biomass purchase payment scenario

Table 6. 5. Expected annual ROI for participating members under the alternative biomass payment distribution when sugar price is in the range of $475-525/tonne

Farm	A	B	C
Acre	100	500	1000
Membership fee, $	20,500	100,500	200,500
Gross profit, $	50,500	252,600	505,300
Expected annual ROI	14.6%	15.1%	15.2%

When the farmers' co-operative's investment into the total capital cost is guaranteed to be returned over 10 years, its expected annual ROI increases to -6.5% from -16.5% as shown in Figure 6.4, while the expected annual ROI for other investors of the biomass project decreases to -3.8% from 6.7%. The probability of achieving a positive annual ROI is 27.1% based on the sugar market price distribution shown in Figure 5.6 and the farmers' co-operative's logistics cost distribution shown in Table 6.3. Under this scenario, if the biorefinery can maintain the product's selling price within the range of $375-525/tonne, the expected annual ROI for the farmers' co-operative and other investors are 1.1% and 1.0%, respectively. The expected annual ROI for three hypothetical members of the farmers' co-operative are listed in Table 6.6. While the expected annual ROIs are lower than the base case scenario's ROI when the sugar price is in the range of $475-525/tonne, it is more likely to achieve the sugar price range of $375-525/tonne.

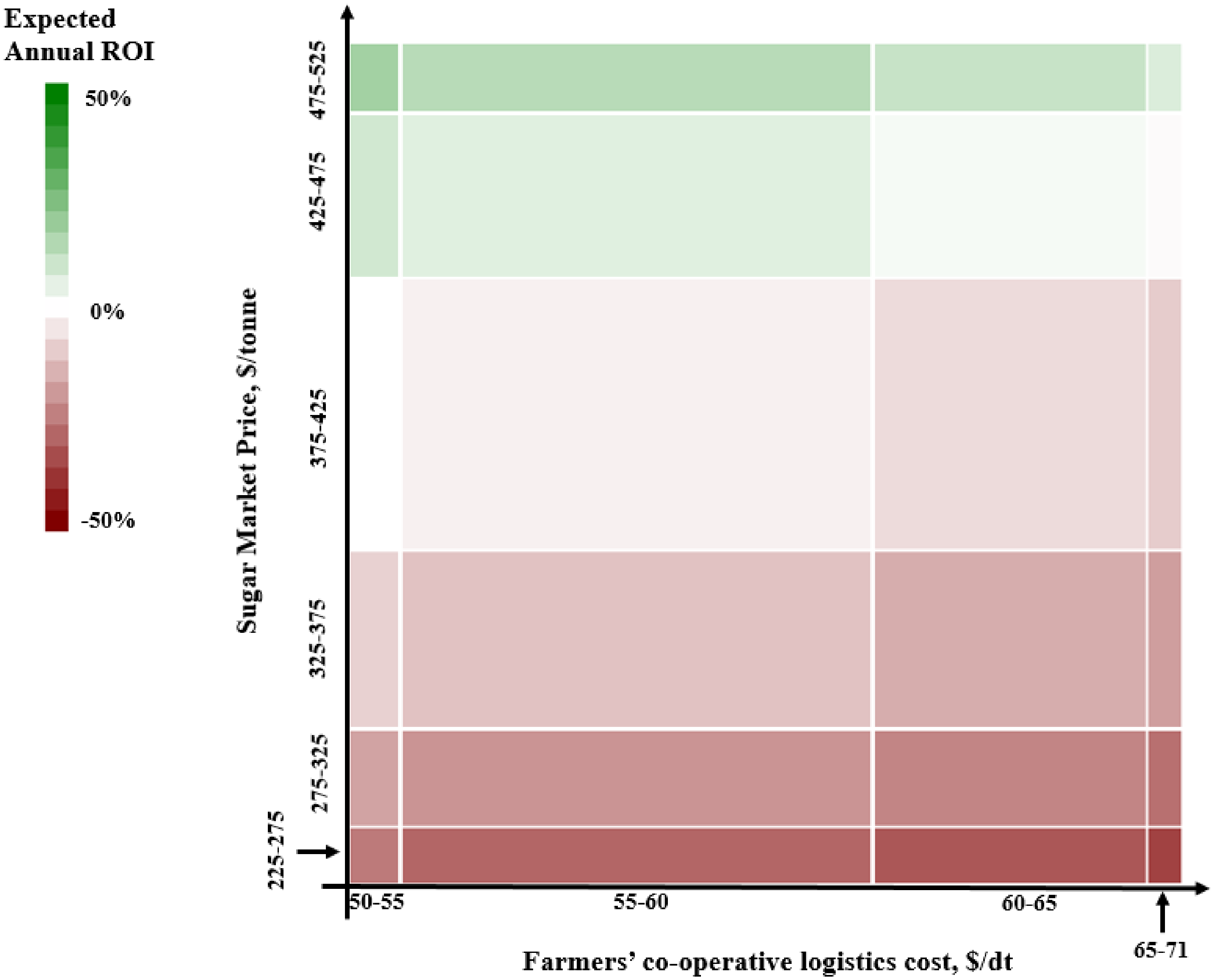


Figure 6. 4. ROI heat map for farmers' co-operative under the guaranteed investment return scenario

Table 6. 6. Expected annual ROI for participating members when sugar price is in the range of $375-525/tonne and a guaranteed return of the farmers' co-operative's investment

Farm	A	B	C
Acre	100	500	1000
Membership fee, $	20,500	100,500	200,500
Gross profit, $	45,260	226,300	452,600
Expected annual ROI	12.1%	12.5%	12.6%

As the maximum supply distance reduces, the farmers' co-operative's logistics cost is expected to decrease due to a reduced transportation and fleet travel distance. However, since the amount of participating corn fields remains at 46,000 acres, the required farm participation rate is expected to increase. At a maximum supply distance of 75 km (instead of 90 km in the base case scenario), the logistics cost distribution for supplying 63,000 dt corn stover is shown in Table 6.7. The logistics costs for participating corn field owners and the biorefinery are the same as they are in the base case scenario, because they are not related to the maximum supply distance. The maximum, average and minimum logistics costs for the farmers' co-operative reduce to$64.12/dt, $53.00/dt and $45.42/dt from $70.42/dt, $59.30/dt and $51.72/dt, respectively. As a result, the expected annual ROI for the farmers' co-operative increased to -13.1% from -16.5% as shown in Figure 6.5, while the expected annual ROI for other investors of the biomass project remains 6.7%, because the reduction in maximum supply distance does not impact the biorefinery's logistics costs. The probability of achieving a positive annual ROI is 9.4% based on the sugar market price distribution shown in Figure 5.6 and the farmers' co-operative's logistics cost distribution shown in Table 6.7. If the biorefinery can maintain the product's selling price within the range of $425-525/tonne, the expected annual ROI for the farmers' co-operative is 0.7%. When this is achieved, the expected annual ROI for other investors of the biomass project is 13.8% and the expected annual ROI for three hypothetical members of the farmers' co-operative are listed in Table 6.8. While the expected annual ROIs are lower than the base case scenario's ROI when the sugar price is in the range of $475-525/tonne, it is more likely to achieve the sugar price range of $425-525/tonne.

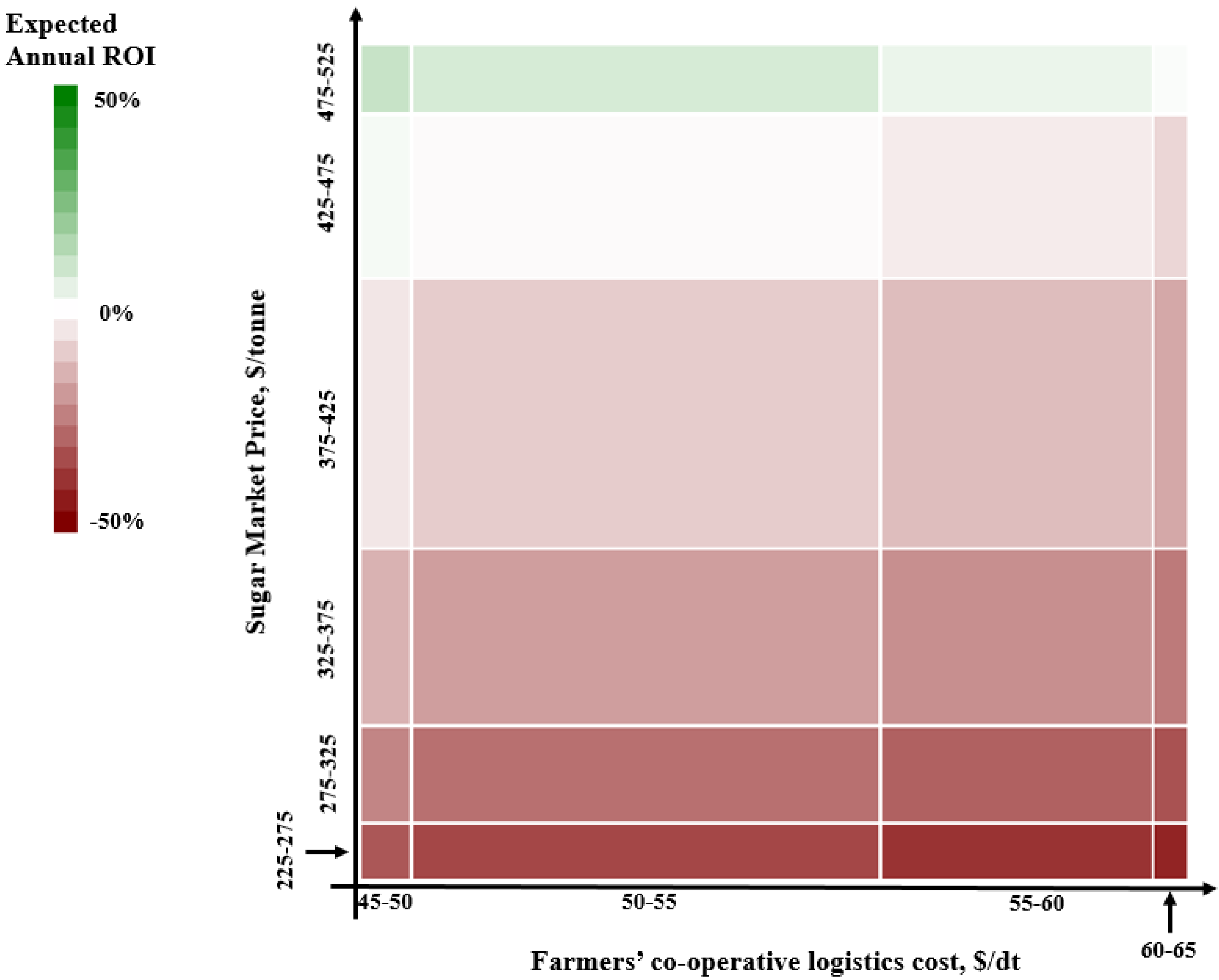


Figure 6. 5. ROI heat map for the farmers' co-operative with a maximum supply distance of 75km

Table 6. 7. The logistics costs of 63,000 dt corn stover within 75 km distance to the biorefinery

	Parties involved in the supply chain		
	Farmers	Farmers' Co-operative	Biorefinery
Maximum logistics costs, $/dt	12.05	64.12	25.79
Average logistics costs, $/dt	12.05	53.00	20.90
Minimum logistics costs, $/dt	12.05	45.42	16.86

Table 6. 8. Expected annual ROI for participating members with a maximum supply distance of 75km and sugar price is in the range of $425-525/tonne

Farm	A	B	C
Acre	100	500	1000
Membership fee, $	20,500	100,500	200,500
Gross profit, $	44,200	221,100	442,200
Expected annual ROI	11.6%	12.0%	12.1%

6.5 Discussion

While the traditional principles of co-operative are retained, the new generation of co-operatives prioritize members' economic benefits by exercising its increased bargaining power and market share. In the co-operative structured analyzed in this chapter, the co-operative does not only manage the biomass supply operation and pricing for its members, but also invests into the biorefinery's capital in order to take shares of the biorefinery's annual net profit and distribute the profit among its members. Under this structure, while the biorefinery still needs to face fluctuations in sugar market price, the standard deviation of corn stover delivered costs has been reduced to $1.42/dt from $6.46/dt. However, the financial risk associated with the variance in corn stover supply operations cannot be eliminated due to the complex and dynamic nature of agriculture practices. It is passed onto the farmers' co-operative since it becomes the farmers' co-operative's responsibility to manage the supply chain operations.

In the base case scenario, when the variances in supply chain operations and sugar market price are both considered, the economic profits and the degree of risk heavily favours the biorefinery's investors as the expected annual ROI are -16.5%. and 6.7% for the farmers' co-operative and other investors of the biomass project, respectively. The biorefinery relies on the farmers' co-operative to secure the biomass supply at a stable quantity, quality and price. In addition, the farmers' co-operative also invests over 40% of the biorefinery's total capital. Therefore, the farmers' co-operative should be able to exercise its bargaining power to form a more economically sustainable business structure to better protect its members' financial interests.

While an alternative biomass payment distribution can improve the farmers' co-operative's economics and reducing the supply radius (from 90km to 75km) can reduce the variance in the supply system operations managed by the farmers' co-operative, better improvement in the expected annual ROI for the farmers' co-operative comes from a guaranteed capital investment return over 10 years. However, it is beyond the scope of this chapter to determine what is the most optimal business structure to be formed between the biorefinery and the farmers' co-operative. In addition, the impact of variation in other economic parameters, such as interest rate, equity-to-loan ratio, lignin market price, farmers' co-operative's administration costs, are not investigated. The purpose of this chapter is to illustrate how the developed quantified economic performance and risk analysis approach can help determine the impact of an alternative business structure or risk mitigation strategy.

The results from this chapter also shows that the economic sustainability and profitability of the biomass project, for both of the farmers' co-operative and other investors, relies on whether the biorefinery can secure a long-term consumer of the produced sugar in the price range of $425-575/tonne or not. Within this sugar price range, the farmers' co-operative and other investors of the biomass project are both more likely to achieve a more satisfying annual ROI (over 10%). This price range may be achievable if local business and political supports and economic subsidies are available.

6.6 Conclusion

In this chapter, it is observed that while it is important for the farmers' co-operative to improve the operation efficiency and reduce operation cost, the fluctuations in the product's market price also impacts the economic performance of the biorefinery and the farmers' co-operative. Due to the small production capacity of the biorefinery in comparison to the global market's capacity, the biorefinery is unlikely to have any significant influence on the product's market price. As a result, it can be critical to the economical success of the biorefinery and the farmers' co-operative if they can secure a long-term buyer at a more stable price with the supports from local community, industry and government.

Although the analysis performed in this chapter is based on the Southwestern Ontario case study, the results can be extracted to apply to other biorefinery projects utilizing crop residues as their feedstock. One limitation of this study is that the economical benefits to the local community and the potential environment benefits are not included in this study, but they may provide additional motivations for regional policy makers to support the biorefinery and the farmers' co-operative's operation in terms of providing favourable policies and taxation, granting funding towards the initial capital and helping the biorefinery to secure a long-term buyer at a relatively stable price. In addition, the impact of variation in other economic parameters, such as interest rate, equity-to-loan ratio, lignin market price, farmers' co-operative's administration costs, are not investigated.

Chapter 7. Conclusion and Recommendations

7.1 Conclusions

The emerging biomass industry has the potential of facilitating a region's economic, social and environmental development, but the industry also faces challenges in biomass supply system and product market. While there exists a rich body of knowledge analyzing local and regional biomass availability applying both deterministic and stochastic models, there is a lack of quantitative discussion considering volatility in the supply chain and the product market at the same time. As a result, the unique contribution of this research is a proposed systematic approach on the development of a risk heat map matrix for risk analysis and methods of mitigating risks for biomass projects.

One of the primary challenges for a biomass project to achieve commercial-scale is to establish a biomass supply system that can meet the long-term biomass demand of the biorefinery in a cost-efficient manner. In general, a processing facility often benefits from the increased capacity quantified by the scale factor or the economy of scale, but a number of previous studies have illustrated such benefits can be hindered as the biomass delivered cost could significantly go up with the increase in the size of the facility. The economic performance associated with three biorefinery capacities (LS at 310,000 dt/year or 860 dt/day, MS at 187,200 dt/year or 520 dt/day and SS at 63,000 dt/year or 175 dt/day) was compared in an industrial-size case study in Southwestern Ontario. The average stover delivered costs were determined to be \$82.09/dt, \$87.49/dt and \$93.75/dt for the SS, MS and LS scenarios, respectively. The probability of achieving the target corn stover delivered cost is estimated to be 45.5%, 9.2% and 0.3% for the SS, MS and LS scenarios, respectively. In addition, the increase in the required capital costs to develop a dedicated logistics equipment fleet is estimated to be much greater than the increase in the delivered costs as the size of the biorefinery increases. The upfront capital costs are estimated to be \$6.72, 21.83 and 35.51 million in the SS, MS and LS scenarios, respectively.

Besides the fluctuations in the capital and operational costs of the supply system, volatilities in the bio-product's market price cannot be underestimated either. The combination of an increased sugar market price and reduced corn stover delivered cost is more likely to achieve a higher expected annual ROI. The results from the developed analysis approach show that as the farm participation rate increases, the corn stover delivered cost distribution shifts towards a lower range of costs ($75-85/dt and $85-95/dt) primarily due to the decrease in the size of the supply area. It is observed that while increasing farm participation rate is economically beneficial to the biorefinery, there are more economic benefits if the sugar market price is in the favourable range (e.g. $375+/tonne). As the expected annual ROI increases, a portion of this economic benefit can be shared with biomass producers to increase their willingness to participate in the biomass supply system. In the case of shifting from 20% to 30% participation rate, $2.88/dt is the maximum incentive that can be provided to the corn growers to increase farm participation rate from 20% to 30%. For the cases of shifting from 20% to 40% and 50% participation rate, the maximum incentives are $4.61/dt and $5.11/dt, respectively. One important observation is that there is more than one strategy to achieve a target annual ROI. For instance, if the target annual ROI is over 3%, it can be achieved by either offering an incentive of $1.27/dt to achieve 40% farm participation rate or offering an incentive of $2.53/dt to achieve 50% farm participation rate.

While it is common to consider the FF supply governance structure for biomass projects, an alternative supply governance structure, FCF, can be more efficient in order to achieve the modern concept of a lean supply system. The traditional principles of co-operative focused on sharing labour and resources, but the new generation of co-operatives prioritize members' economic benefits by exercising its increased bargaining power and market share. In the co-operative structured analyzed in this study, the co-operative does not only manage the biomass supply operation and pricing for its members, but also invests into the biorefinery's capital in order to take shares of the biorefinery's annual net profit and distribute the profit among its members. However, the financial risk associated with the variance in corn stover supply operations cannot be eliminated due to the complex and dynamic nature of agriculture practices. It is passed onto the farmers' co-operative since it becomes the farmers' co-operative's responsibility to manage the supply chain operations. The results from this study shows that if the biorefinery can secure a long-term consumer of the produced sugar in the price range of $425-575/tonne, the farmers' co-operative and other investors of the biomass project are both more likely to achieve a more satisfying annual ROI (over 10%).

Overall, the results from applying the developed approach to the industrial case study have achieved the contributions and objectives outlined in this study (Section 1.3). In particular, the systematic economic risk analysis approach developed in this study can facilitate and promote the discussion of operational standards, risk mitigation strategies, business structures and policies among interested parties, such as biomass producers, investors, governments, politicians, engineers, academics and financial institutions. As shown in Figure 7.1, the developed approach includes five steps:

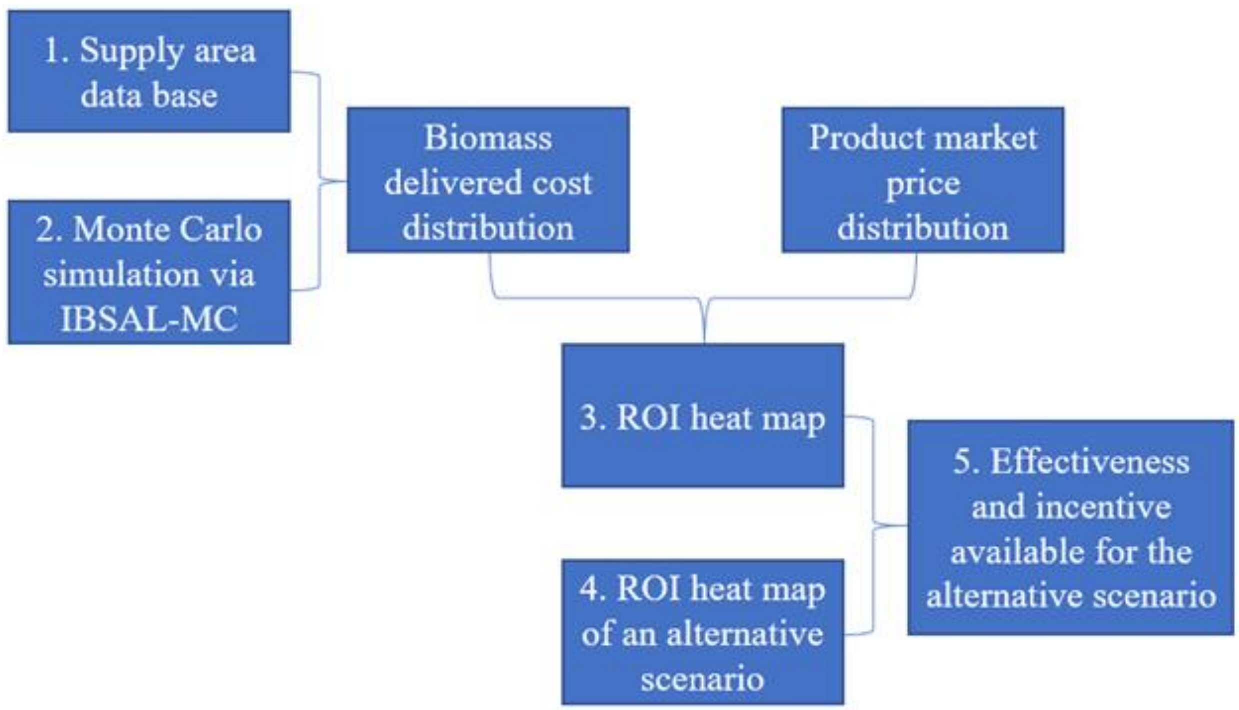


Figure 7. 1. Methodology flow chart

1. Construct the supply area database (geographical).
2. Run Monte Carlo simulation (via IBSAL-MC) to obtain the biomass delivered cost distribution.
3. Combine the biomass delivered cost distribution with the product market price distribution to generate a ROI heat map.
4. Repeat Steps 1 to 3 for an alternative scenario.
5. Compare heat maps from different scenarios to quantify the effectiveness and incentive available for achieving the alternative scenario.

Through the analysis performed in this thesis, while biomass supply security (quantity, quality and unit price) is very important to the establishment of a biorefinery, the fluctuation in product's market price also poses a considerable level of risk to the biorefinery and the biomass suppliers (under both supply governance structures). As a result, it can be critical to the economical success of the biorefinery and the biomass suppliers if they can secure a long-term buyer at a more stable price with the supports from local community, industry and government. The regional policy makers may be motivated to support the development of a biorefinery and a farmers' co-operative as its biomass supplier by the economic, environment and social values it can bring to the local community.

7.2 Strengths and Limitations of the Study

All businesses face challenges and risks in both the supply side and the product market side. This is especially so for the emerging biomass industry. On the supply side, since biomass is not yet a widely traded commodity, every biomass project faces the challenge of establishing a secure supply system (quantity, quality and unit price). Due to the complexity and uncertainties within agriculture activities, the associated risks in the supply system can also be high. On the market side, biomass industry often needs to compete in an established national or global market. With almost no control over the product's market price, the biomass project may face economic risks associated with product price volatility through its lifetime.

The analysis (shown as the following) developed in this study is designed to quantitatively analyze the long term economic performance and risk of a biomass project:

1. Establishment of supply security at an economically feasible capacity.
2. Performing economic performance and risk analysis to understand the impact of fluctuations in biomass supply costs and product market price.
3. Constructing a region biomass supplier co-operative to share the risk and benefits.
4. Seeking local downstream consumers who can purchase the product at a more stable price.

While the analysis performed in this thesis is based on one industrial case study, the methodology can be applied to biomass project in other regions as a general guideline to protect the project's long-term economic wellbeing. The important strengths of the developed methodology are:

1. The methodology, especially gridding, is ideal for any specific region to provide practical results.

2. The application of the Monte Carlo stimulation via IBSAL-MC can capture the stochastic nature of agriculture and supply logistic operations so that the results of the simulation is a biomass delivered cost distribution.
3. The developed economic performance and risk analysis approach can quantify the combined impact of supply and market volatility, and the visualization of the results of the analysis can facilitate communication between all parties involved to develop a reciprocal business plan and risk mitigation strategy.
4. The developed methodology can also be applied to quantitatively analyze the impact of adopting one or more business plans or risk mitigation strategies to achieve a desirable level of robustness.

While the strengths of the developed methodology can facilitate the process for biomass project to move on to industrial scale, there are also some limitations to the applications of this methodology:

1. The developed methodology requires detailed geological information of the supply area under analysis.
2. The level of reliability of the outcome of the Monte Carlo simulation relies on the accuracy of the software used to perform simulations and how practical the values of the coefficients are in the simulations.
3. Due to the stochastic nature of biomass production, the developed methodology aims to assist the development of business plans and risk mitigation strategies that provide acceptable expected investment return instead of an optimized (or maximized) return.
4. The alternative supply governance structure studied, farmers' co-operative, was designed to be reciprocal to secure the biomass project's long-term success and sustainability instead of maximizing any party's economic interests.
5. Lastly, the monetary value of the environmental and social benefits of a biomass project is not included in this study.

7.3 Future Research

The approach developed in this study can benefit parties involved in an industrial scale biomass project, such as biomass producers, investors, governments, politicians, engineers, academics and financial institutions, by quantifying the biomass project's long-term economic performance and risk and assisting them to evaluate and develop corresponding policies, financing, business plans and risk mitigation strategies. At the same time, other important environmental and social considerations can also be critical to a biomass project's success. For example, Ontario launched a cap and trade program to place a cap on Ontario's homes and business GHG emissions and intended to lower the limit over time. However, effective on July 3rd, 2018, the cap and trade regulation was cancelled and all trading of emission allowances was prohibited (Ontario Ministry of the Environment, Conservation and Parks, 2018.). In a future study, it is possible to examine the GHG emission and reduction of sugar production from corn stover via life cycle analysis to establish whether the project could be economically benefitted from the trading of emission allowances under a program like the cap and trade program. This type of studies raises the challenge to quantify the monetary value a biomass project can introduce to the region, and how this value can be converted into incentives for parties involved. The outcome of this direction of future research can better address the three dimensions of sustainability (economic/profit, social/people and environment/planet).

Another direction of future research is to apply the approach to another biomass project in a different region to observe the importance of geographical and social factors that are not considered in this study. Alternatively, the analysis for this study can be performed again to consider the use of both corn stover and winter wheat straws to investigate the benefits of designing a biomass project and supply chain system involving multiple sources of biomass supply.

The results of this study showed that a farmers' co-operative can contribute towards and be benefited from business involvement in a biomass project. However, the organization structure and value of a farmers' co-operative may be connected to the culture of the supply area. It would be more practical and realistic to combine the analysis performed in this study with a designed social survey conducted in the supply area to understand whether the quantified potential economic incentive is sufficient to motivate local biomass producers, and what other benefits the biorefinery and farmers' co-operative can provide to increase local biomass producers' willingness to participate.

Reference List

Abbati de Assis, C., Gonzalez, R., Kelley, S., Jameel, H., Bilek, T., Daystar, J., et al. 2017. Risk management consideration in the bioeconomy. Biofuels, Bioprod. Bioref. 11:549-66, DOI: 10.1002/bbb

AGCO. Viewed on 2018-02-22, via: http://www.agcocorp.com/

Altman, I. and Sanders, D. 2012. Producer willingness and ability to supply biomass: Evidence form the U.S. Midwest. Biomass and Bioenergy 36:176-81.

Altman, I., Bergtold, J., Sanders, D. and Johnson, T. 2015. Willingness to supply biomass for bioenergy production: A random parameter truncated analysis. Energy Economics 47:1-10.

Arbogast, S., Bellman, D., Paynter, J. and Wykowski, J. 2012. Advanced bio-fuels from pyrolysis oilthe impact of economies of scale and use of existing logistic and processing capabilities. Fuel Process Technol, 104:121–6.

Arctic Energy Alliance (AEA). 2009. Supply and Transport Options for Wood Pellets. Canada: Arctic Energy Alliance.

Arnold, U. and Yildiz, O. 2015. Economic risk analysis of decentralized renewable energy infrastructures – A Monte Carlo Simulation approach. Renewable Energy, 77, 227-239.

Association of the Chemical Profession of Ontario. Viewed on 2016-03-31. ACPO Council Electoral Districts, via: http://www.acpo.on.ca/about/council/electoral_e.php

Alghalith, M. 2006. Price and output risk: empirical analysis. Applied Economics Letters 13(6):391-393.

American Society of Agricultural Engineers (ASAE). 2000. Agricultural Machinery Management Data. ASAE Standards 2000, D497.

Athmanathan, A., Emery, I. R., Kuczek, T. and Mosier, N. S. 2015. Impact of Temperature, Moisture and Storage Duration on the Chemical Composition of Switchgrass, Corn Stover and Sweet Sorghum Bagasse. Bioenerg. Res., 8, 843-856.

Alnur Auli, N., Sakinah, M., Mustafa Al Bakri, A. M., Kamarudin, H. and Norazian, M. N. 2013. Simulation of Xylitol Production: A Review. Australian Journal of Basic and Applied Sciences, 7:5: 366-372.

Bafrani, M. P. 2010. Citrus Waste Biorefinery: Process Development, Simulation and Economic Analysis. Doctoral thesis. Department of Chemical and Biological Engineering, Chalmers University of Technology, Sweden.

Bartkute, A. and Tolocka, E. 2013. Risk Management Improvement of Engineering Projects in Woodworking Industry. DOI: 10.3846/mla.2013.98

Bergtold, J. S., Fewell, J. and Williams, J. 2014. Farmers' willingness to produce alternative cellulosic biofuel feedstocks under contract in Kansas using stated choice experiments. BioEnergy Research 7(3):876-884.

BIC. Viewed on 2018-02-22, via: https://www.bincanada.ca/

Birrell, S. J., Karlen, D. L. and Wirt, A. 2014. Development of Sustainable Corn Stover Harvest Strategies for Cellulosic Ethanol Production. Bioenerg. Res., 7, 509-516.

Bosch, R., van de Pol, M. and Philp, J. 2015. Define biomass sustainability. Nature. 523:7562, 526-527.

Brechbill, S. C. and Tyner W. E. 2008. The Economics of Biomass Collection, Transportation and Supply to Indiana Cellulosic and Electric Utility Facility. Department of Agricultural Economics Purdue University.

Chartered Global Management Accountant (CGMA). 2012. CGMA tools: how to communicate risks using a heat map.

Chen, J., Sohal, A. S. and Prajogo, D. I. 2016. Supply risk mitigation: a multi-theoretical perspective. Production Planning & Control, 27:10, 853-863, DOI: 10.1080/09537287.2016.1147620

Chiu, C. H. and Choi, T. M. 2016. Supply chain risk analysis with mean-variance models: a technical review. Ann Oper Res, 240, 489-507. DOI:10.1007/s10479-013-1386-4.

Colliers International. 2017. London. Viewed on 2017-01-15, via: http://www.collierscanada.com/en/offices/london

Comet Biorefining. Viewed on 2018-06-10, via: https://cometbiorefining.com/

CSPC. Viewed on 2018-02-22, via: https://www.cspcoop.com/

Cundiff, J. S., Grisso, R. D. and Judd J. 2009. Operations at satellite storage locations (SSL) to deliver round bales to a biorefinery plant. ASABE Paper No 958962009

Curtis, A. (2013). An overview of contract farming. Accessed on 2017-10-13, via: http://www.gillespiemacandrew. co.uk

De Laporte, A. V., Weersink, A. J. and McKenney, D. W. 2016. Effects of supply chain structure and biomass prices on bioenergy feedstock supply. Applied Energy, 183, 1053-1064.

De Vries, R. P., Visser, J. 2001. Aspergillus enzymes involved in degradation of plant cell wall polysaccharides. Microbiol. Mol. Biol. Rev. 65:497–522.

Deleris, L. A. and Erhun, F. 2005. Risk management in supply networks using Monte-Carlo simulation. Proceedings of the 2005 Winter Simulation Conference.

Dien, B. S., Jung, H. J. G., Vogel, K. P., Casler, M. D., Lamb, J. F. S., Iten, L. B., Mitchell, R. B., Sarath, G. 2006. Chemical Composition and Response to Dilute-Acid Pretreatment and Enzymatic Saccharification of Alfalfa, Reed Canarygrass, and Switchgrass. Biomass Bioenergy, 30, 880-891.

Duffy, R. and Marchand, L. 2013. Development of a Business Case for a Cornstalks to Bioprocessing Venture – Final Report. University of Guelph, Ridgetown Campus.

DuPont. 2016. Creating sustainable supply chains for cellulosic biofuels. Accessed o 2016-03-14 via: http://www.biofuelsdigest.com/bdigest/2014/07/17/creating-sustainable-supplychains-for-cellulosic-biofuels

Ebadian, M. 2013. Optimal Design of Agricultural Biomass Supply Chain for a Cellulosic Ethanol Plant. The University of British Columbia.

Ebadian, M., Sowlati, T., Sokhansanj, S., Stumborg, M. and Townley-Smith, L. 2011. A new simulation model for multi-agricultural biomass logistics system in bioenergy production. Biosystems Engineering, 110:280-90.

Edward, W. 2014. Estimating a Value for Corn Stover. Iowa State University. Accessed on 2015-08-09, via: https://www.extension.iastate.edu/agdm/crops/html/a1-70.html

Elghali, L., Clift, R., Sinclair, P., Panoutsou, C. and Bauen, A. 2007. Developing a Sustainability Framework for the Assessment of Bioenergy Systems. Energy Policy, 35:12, 6075-6083.

Emery, I. and Mosier, N. 2015. Direct Emission of Methane and Nitrous Oxide from Switchgrass and Corn Stover: Implications for Large-Scale Biomass Storage. GCB Bioenergy, 7, 865-876.

Environmental Justice Atlas. 2016. Chemical Valley, Sarnia (Ontario, Canada). Accessed on 2016-03-31, via: https://ejatlas.org/conflict/chemical-valley-sarnia-ontario-canada

Faisal, M. N., Banwet, D. K. and Shankar, R. 2006. Mapping supply chains on risk and customer sensitivity dimensions. IMDS 106(6):878-95.

Fisher, P. 1997. The pixel: A snare and a delusion, International Journal of Remote Sensing, 18:3, 679-685, DOI: 10.1080/014311697219015

Galik, C. S., Abt, R. C., Latta, G., Meley, A. and Henderson, J. D. 2016. Meeting renewable energy and land use objective through public-private biomass supply partnerships. Applied Energy 172: 264-74

Gerbens-Leenes, W., Hoekstra, A. Y. and van der Meer, T. H., 2009. The water footprint of bioenergy. Proceedings of the National Academy of Sciences (PNAS), 106:25, 10219-10223.

Giarola, S., Bezzo, F. and Shah, N. 2013. A Risk Management Approach to the Economic and Environmental Strategic Design of Ethanol Supply Chains. Biomass and Bioenergy, 58, 31-51.

Giuntoli, J., Boulamanti, A. K., Corrado, S., Motegh, M., Agostini, A. and Baxter, D. 2013. Environmental Impacts of Future Bioenergy Pathways: The Case of Electricity from Wheat Straw Bales and Pellets. GCB Bioenergy, 5, 497-512.

Gnanasounou, E., Dauriat, A., Villegas, J. and Panichelli, L. 2009. Life Cycle Assessment of Biofuels: Energy and Greenhouse Gas Balances. Bioresource Technology, 100, 4919-4930.

Goetschalckx, M., Huang, E. and Mital, P. 2012. Robust Global Supply Network Design. Information Knowledge Systems Management, 11:1.

Goetschalckx, M., Huang, E. and Mital, P. 2013. Trading off Supply Chain Risk and Efficiency through Supply Chain Design. DOI: 10.1016/j.procs.2013.01.069

Gold, S. and Seuring, S. 2011. Supply Chain and Logistics Issues of Bio-energy Production. Journal of Cleaner Production, 19, 32-42.

Golecha, R. and Gan, J. 2016a. Optimal contracting structure between cellulosic biorefineries and farmers to reduce the impact of biomass supply variation: game theoretic analysis. Biofuels, Bioprod. Bioref., 10, 129–138, DOI: 10.1002/bbb.1626

Golecha, R. and Gan, J. 2016b. Effects of corn stover year-to-year supply variability and market structure on biomass utilization and cost. Renewable and Sustainable Energy Reviews, 57, 34-44.

Google Map. 2015. Ontario. Accessed on 2015-09-30, via: https://www.google.ca/maps/place/Ontario/@48.5105322,-88.2426405,5z/data=!4m5!3m4!1s0x4cce05b25f5113af:0x70f8425629621e09!8m2!3d51.253775!4d-85.3232139

Graham, R. L., Nelson, R., Sheehan, J., Perlack, R. D. and Wright, L. L. 2007. Current and Potential U.S. Corn Stover Supplies. Agronomy Journal, 99, 1-11.

Granjo, J., Duarte, B. P. M. and Oliveira, N. 2015. Soybean biorefinery: Process simulation and alaysis. Chemical Engineering Transactions, 45:583-588.

Greenland, S. 2001. Sensitivity analysis, Monte Carlo risk analysis, and Bayesian uncertainty assessment. Risk Analysis, 21:4, 579-583.

Grooms, L. 2014. Harvesting Corn Stover in Sustainable Ways. Farm Industry News, 2014-October-13.

Gutesa, S. 2013. Using GIS and intelligent transportation tools for biomass supply chain modeling and cost assessment. Master's Thesis, Agricultural Engineering, Iowa State University, Ames, Iowa.

Hamedani, H. K. 2015. Logistics Modeling of Biomass Supply Chain in Ontario. The University of British Columbia.

Hart, C. and Edwards, W. 2013. Corn Stover: Economic Considerations. Iowa Corn Stover Harvest Meeting. Accessed on 2015-10-01, via: http://webcache.googleusercontent.com/search?q=cache:Z4XEw5MsPugJ:www2.econ.iastate.edu/faculty/hart/presentations/Hart-IA130306.ppt+&cd=1&hl=en&ct=clnk&gl=ca

Hellqvist, L. 1996. Conversion of straw to ethanol - Optimisation of the pretreatment step Examensarbete, Department of Chemical Engineering I, Lund Sweden.

Hess, J. R., Kenney, K. L., Wright, C. T. and Perlack, R. 2009. Corn Stover Availability for Biomass Conversion: Situation Analysis. Cellulose, 16, 599-619.

Hettinga, W. G., Junginger, H. M., Dekker, S. C., Hoogwijk, M., McAloon, A. J. and Hicks, K. B. 2009. Understanding the Reductions in US Corn Ethanol Production Costs: An Experience Curve Approach. Energy Policy, 37, 190-203.

Hsu, T. C., Guo, G. L., Chen, W. H. and Hwang, W. S. 2010. Effect of dilute acid pretreatment of rice straw on structural properties and enzymatic hydrolysis. Bioresource Technology, 101:13:4907-4913.

Huang, H., Faulkner, D. B., Berger, L. L. and Eckhoff, S. R. 2012. Harvest Date Influence on Dry Matter Yield and Moisture of Corn and Stover. American Society of Agricultural and Biological Engineers, 55:2, 592-598.

Igathinathane, C., Womac, A. R., Pordesimo, L. O. and Sokhansanj, S. 2008. Mold Appearance and Modeling on Selected Corn Stover Components during Moisture Sorption. Bioresource Technology, 99, 6365-6371.

IndexMundi. 2017. Sugar price. Accessed on 2017-07-15, via: http://www.indexmundi.com/commodities/?commodity=sugar&months=360

IndexMundi. 2017. Crude oil price. Accesed on 2017-07-15, via: http://www.indexmundi.com/commodities/?commodity=crude-oil&months=180

Ingalls, R. G. 1998. The value of simulation in modeling supply chains. In proceedings of the 1998 Winter Simulation Conference.

Izquierdo, S., Dopazo, C. and Fueyo, N. 2010. Supply-cost curves for geographically distributed renewable-energy resources. Energy Policy, 38, 667-672.

Jeschke, M. and Heggenstaller, A. 2012. Sustainable Corn Stover Harvest for Biofuel Production. Crop Insights, 22:5, 1-6.

Jorgensen, H., Kristensen, J. B., Felby, C. 2017. Enzymatic conversion of lignocellulose into fermentable sugars: Challenges and opportunities. Biofuels Bioprod. Biorefin. 1:119–134.

Julian, A. and Cardona, C. A. 2011. Process Simulation of Fuel Ethanol Production from Lignocellulosics using Aspen Plus. Ind. Eng. Chem. Res., 50:10:6205-6212.

Jupesta, J., Harayama, Y. and Parayil, G. 2011. Sustainable Business Model for Biofuel Industries in Indonesia. Sustainability Accounting, Management and Policy Journal, 2:2, 231-247.

Karlen, D. L., Birrell, S. J. and Hess, R. 2011. A Five-Year Assessment of Corn Stover Harvest in Central Iowa, USA. Soil & Tillage Research, 115-116, 47-55.

Karlen, D. L., Birrell, S. J., Johnson, J. M. F., Osborne, S. L., Schumacher, T. E., Varvel, G. E., Ferguson, R. B., Novak, J. M., Fredrick, J. R., Baker, J. M., Lamb, J. A., Adler, P. R., Roth, G. W., Nafziger, E. D. 2014. Multilocation Corn Stover Harvest Effects on Crop Yields and Nutrient Removal. Bioenerg. Res., 7, 528-539.

Karlen, D. L., Kovar, J. L. and Birrell, S. J. 2015. Corn Stover Nutrient Removal Estimates for Central Iowa, USA. Sustainability, 7, 8621-8634.

Karunanithy, C., Muthukumarappan, K. and Donepudi, A. 2013. Moisture Sorption Characteristics of Corn Stover and Big Bluestem. Journal of Renewable Energy, 2013, 1-12.

Kumar, A. and Sokhansanj, S. 2007. Switchgrass (Panicum vigratum L.) delivery to a biorefinery using integrated biomass supply analysis and logistics (IBSAL) model. Bioresour Technol, 98:1033–44.

Lauer, C., McCaulou, J. C., Sessions, J. and Capalbo, S. M. 2015. Biomass supply curves for western juniper in Central Oregon, USA, under alternative business models and policy assumptions. Forest Policy and Economics 59:75-82.

Leboreiro, J. and Hilaly, A. K. 2013. Analysis of Supply Chain, Scale Factor, and Optimum Plant Capacity for the Production of Ethanol from Corn Stover. Biomass and Bioenergy, 54, 158-169.

Leduc, S., Starfelt, F., Dotzauer, E., Kindermann, G., McCallum, I., Obersteiner, M. and Lundgren, J. 2010. Optimial Location of Lignocellulosic Ethanol Refineries with Polygeneration in Sweden. Energy, 35, 2709-2716.

Ledoit, O. and Wolf, M. 2008. Robust performance hypothesis testing with the Sharpe ratio. Journal of Empirical Finance, 15, 850-859.

Li, X., Mupondwa, E., Panigrahi, S., Tabil, L., Sokhansanj, S. and Stumborg, M. 2012. A Review of Agricultural Crop Residue Supply in Canada for Cellulosic Ethanol Production. Renewable and Sustainable Energy Reviews, 16, 2954-2965.

Li, B., Ou, L., Dang, Q., Meyer, P., Jones, S., Brown, R. et al. 2015. Techno-economic and uncertainty analysis of in situ and ex situ fast pyrolysis for biofuel production. Bioresour Technol 196:49–56.

Lynn, M. W., Bonner, I. J., Hoover, A. N., Emerson, R. M. and Smith, W. A. 2014. Influence of Airflow on Laboratory Storage of High Moisture Corn Stover. Bioenerg. Res., 7, 1212-1222.

Ma, S. and Eckhoff, S. R. 2012. Economy of Scale for Biomass Refineries: Commodity vs. Contract Pricing, Area Utilization Factor, and Energy Crops. American Society of Agricultural and Biological Engineers, 55:2, 599-607.

Mahmudi, H. and Flynn, P. C. 2006. Rail vs. Truck Transport of Biomass. Applied Biochem. And Biotech., 129:1-3, 88-103.

Mann, L., Tolbert, V. and Cushman, J. 2002. Potential Environmental Effects of Corn (Zea mays L.) Stover Removal with Emphasis on Soil Organic Matter and Erosion. Agriculture, Ecosystems and Environment, 89, 149-166.

Manstretta, V. and Rossi, V. 2015. Modeling the Effect of Weather on Moisture Fluctuations in Maize Stalk Residues, an Important Inoculum Source for Plant diseases. Agricultural and Forest Meteorology, 207:1, 83-93.

Marchand, L. 2015. Cost Assessment for Cornstalk Supply Chain for Bioprocessing Purposes. University of Guelph, Ridgetown Campus.

Mark, T., Darby, P. and Salassi, M. 2009. A comparison of pricing strategies for cellulosic ethanol processors: A simulation approach. The American Agricultural Economis Association Annual Meetings, Milwaukee, Wisconsin, July 26-28, 2009.

Martinez-Kawas, A. 2013. A feasibility study of post-harvest handling, storage and logistics of bioenergy crops. Ph.D. thesis. Kansan State University.

Marvin, W. A., Schmidt, L. D., Benjaafar, S., Tiffany, D. G. and Daoutidis, P. 2012. Economic optimization of a lignocellulosic biomass-to-ethanol supply chain. Chemical Engineereing Science, 67, 68-79.

McDonald, I. 2010. Agricultural Residues – Crops, Harvesting, Logistics, Soil Sustainability. OMAFRA. Accessed on 2015-09-05, via: http://www.ofa.on.ca/uploads/userfiles/files/ian%20mcdonald.pdf

Miranda, T., Montero, I., Sepulveda, F. J., Arranz, J. I., Rojas, C. V. and Nogales, S. 2015. A Review of Pellets from Different Sources. Materials, 8, 1413-1427.

Mode, C. J. and Gallop, R. J. 2008. A review on Monte Carlo simulation methods as they apply to mutation and selection as formulated in Wright–Fisher models of evolutionary genetics. Mathematical Biosciences, 211:2:205-225.

Mohr, A., Beuchelt, T., Schneider, R. and Virchow, D. 2016. Food security criteria for voluntary biomass sustainability standards and certifications. Biomass and Bioenergy, 89, 133-145.

Montross, M. D. and Crofcheck, C. L. 2004. Effect of Stover Fraction and Storage Method on Glucose Production during Enzymatic Hydrolysis. Bioresource Technology, 92, 269-274.

Morey, R. V., Kaliyan, N., Tiffany, D. G. and Schmidt, D. R. 2010. A Corn Stover Supply Logistics System. Applied Engineering in Agriculture, 26:3, 455-461.

Morrone, M., Stuart, B. J., McHenry, I. and Buckley, G. L. 2009. The challenges of biofuels from the perspective of small-scale producers in Ohio. Energy Policy 37:522-30.

Mupondaw, E., Li, X., Tabil, L., Phani, A., Sokhansanj, S., Stumborg, M., Gruber, M. and Laberge, S. 2012. Technoeconomic Analysis of Wheat Straw Densification in the Canadian Prairie Province of Manitoba. Bioresource Technology, 1:10, 355-363.

Nguyen, M. H. and Prince, R. G. H. 1996. A Simple Rule for Bioenergy Conversion Plant Size Optimization: Bioethanol from Sugar Cane and Sweet Sorghum. Biomass and Bioenergy, 10:5/6, 361-365.

Nilsson, D., Bernesson, S. and Hansson, P. 2010. Pellet Production from Agricultural Raw Materials – A Systems Study. Biomass and Bioenergy, 35, 679-689.

Niu, B., Jin, D. and Pu, X. 2016. Coordination of channel members' efforts and utilities in contract farming operations. European Journal of Operational Research, 255:869-883.

Ontario Ministry of Agriculture, Food and Rural Affairs (OMAFRA). Viewed in October, 2015, via: http://www.omafra.gov.on.ca/english/crops/index.html

Ontario Ministry of the Environment, Conservation and Parks. Viewed on 2018-08-12, via: https://www.ontario.ca/page/cap-and-trade

Oo, A. and Lalonde, C. 2012. Biomass Crop Residues Availability for Bioprocessing in Ontario. Ontario: Western Sarnia-Lambton Research Park.

Oyedeji, O., Sokhansanj, S. and Webb, E. 2015. Spatial Analysis of Stover Moisture Content during Harvest Season in the United States. Unpublished work written to be submitted to Transactions of the ASABE.

Perlack, R. D. and Turhollow, A. F. 2002. Assessment of Options for the Collection, Handling, and Transport of Corn Stover. Oak Ridge: Oak Ridge National Laboratory.

Petter, R. and Tyner, W. E. 2014. Technoeconomic and policy analysis for corn stover biofuels. ISRN Economics, 2014:1–13.

POET. 2014. Biomass Program Overview. POET Biomass. Accessed on 2015-08-10, via: http://poet-dsm.com/biomass

Prakash, S., Soni, G., Rathore, A. P. S. 2017. A critical analysis of supply chain risk management content: a structured literature review. Journal of Advances in Management Research, 14:1, 69-90.

Pries, F., Talebi, A., Schillo, R. S. and Lemay, M. A. 2016. Risk s affecting the biofuels industry: A US and Canadian company perspective, Energy Policy. 97, 93-101.

Qazi, A., Quigley, J., Dickson, A. and Ekici, S. O. 2017. Exploring dependency based probabilistic supply chain risk measures for prioritising interdependent risks and strategies. European Journal of Operational Researech, 259, 189-204.

Qualls, D. J., Jensen, K. L., Clark, C. D., English, B. C., Larson, J. A. and Yen, S. T. 2012. Analysis of factors affecting willingness to produce switchgrass in the southeastern United States. Biomass and Bioenergy 39:159-67

Quintero, J. A. and Cardona, C. A. 2011. Process simulation of fuel ethanol production from lignocellulosics using Aspen Plus. Ind. Eng. Chem. Res, 50:10:6205-6212.

Roni, M., Eksioglu, S. D., Searcy, E. and Jha, K. 2014. A Supply Chain Network Design Model for Biomass Co-Firing in Coal-Fired Power Plants. Transportation Research Part E, 61, 115-134.

Schmitt, A. and Singh, M. 2009. Quantifying supply chain disruption risk using Monte Carlo and discrete-event simulation. Proceedings of the 2009 Winter Simulation Conference.

Schuhmacher, F. and Breuer, W. 2014. When all risk-adjusted performance measures are the same: in praise of the Sharpe ratio # a comment. Quantitative Finance, 14:5, 775-776. doi: 10.1080/14697688.2013.872284

Schwab, A., Warner, E. and Lewis, J. 2016. 2015 Survey of Non-Starch Ethanol and Renewable Hydrocarbon Biofuels Producers. National Renewable Energy Laboratory.

Shah, A. 2013. Techno-economic analysis and life cycle assessment of the corn stover biomass feedstock supply chain system for a Midwest-based first generation cellulosic biorefinery. PhD Thesis, Agricultural and Biosystems Engineering (Advanced Machinery Engineering), Iowa State University.

Shah, A. and Darr, M. 2014. Corn Stover Storage Losses. Iowa State University. Accessed on 2015-08-21, via: https://store.extension.iastate.edu/Product/Corn-Stover-Storage-Losses

Shah, A., Darr, M., Webster, K. and Hoffman, C. 2011. Outdoor Storage Characteristics of Single-Pass Large Square Corn Stover Bales in Iowa. Energies, 4, 1687-1695.

Sharpe, W. F. 1998. Morningstar's Risk-Adjusted Ratings. Financial Analysts Journal, 54:4, 21-33.

Shinners, K. J., Binversie, B. N., Muck, R. E. and Weimer, P. J. 2007. Comparison of Wet and Dry Corn Stover Harvest and Storage. Biomass and Bioenergy, 31:4, 211-221.

Skott, T. 2011. Straw to Energy: Status, Technologies and Innovation in Denmark 2011. Denmark: Innovation Network for Biomass.

Smeets, E. M. W., Faaij, A. P. C., Lewandowski, I. M. and Turkenburg, W. C. 2007. A Bottom-up Assessment and Review of Global Bio-Energy Potentials to 2050. Progress in Energy and Combustion Science, 33, 56-106.

Sokhansanj, S., Mani, S., Stumborg, M., Samson, R. and Fenton, J. 2006a. Production and Distribution of Cereal Straw on the Canadian Prairies. Can. Biosyst. Eng., 48:3, 39-46.

Sokhansanj, S., Kumar, A., Turhollow, A. F., 2006b. Development and implementation of integrated biomass supply analysis and logistics (IBSAL) model. Biomass and Bioenergy Journal, 30, 838–47.

Stephen, J. D., Sokhansanj S., Bi, X., Sowlati, T., Kloeck, T. and Townley-Smith, L., et al. 2010. The impact of agricultural residue yield range on the delivered cost to a biorefinery in the Peace River region of Alberta, Canada. Biosyst Eng, 105:298–305.

Sultana, A., Kumar, A. and Harfield, D. 2010. Development of Agri-pellet Production Cost and Optimum Size. Bioresource Technology, 101, 5609-5621.

Susilowati, E., Oktaviani, R., Arifin, B. and Arkeman, Y. 2014. The evaluation of cooperative’s role in soybean supply chain: A case study on tofu and tempeh cooperatives in Indonesia. International Journal of Administrative Science & Organization, 21:2:121-127

Takata, S. and Yamanaka, M. 2013. BOM Based Supply Chain Risk Management. CIRP Annals – Manufacturing Technology, 62, 479-482.

Taniguchi, M., Suzuki, H., Watanabe, D., Sakai, K., Hoshino, K. and Tanaka, T. 2005. Evaluation of pretreatment with Pleurotus ostreatus for enzymatic hydrolysis of rice straw. Journal of Bioscience and Bioengineering, 100:6:637-643.

Tao, L., Schell, D., Davis, R., Tan, E., Elander, R. and Bratis, A. 2014. NREL 2012 Achievement of Ethanol Cost Targets: Biochemical Ethanol Fermentation via Dilute-Acid Pretreatment and Enzymatic Hydrolysis of Corn Stover. U.S.: National Renewable Energy Laboratory.

Tavenar, T. 2011. Biomass to Energy Projects in Kansas. Kansas: 2011 Kansas Environmental Conference.

Tenzin, G. and Natsuda, K. 2016. Social capital, household income, and community development in Bhutan: a case study of a dairy cooperative, Development in Practice, 26:4, 467-480, DOI: 10.1080/09614524.2016.1161731

Terry, A. and Ogg, M. 2017. Restructuring the Swazi sugar industry: The changing role and political significance of smallholders, Journal of Southern African Studies, 43:3, 585-603, DOI: 10.1080/03057070.2016.1190520

Theerarattananoon, K., Xu, F., Wilson, J., Ballard, R., Mckinney, L., Staggenborg, S. Vadlani, P., Pei, Z. J. and Wang, D. 2011. Physical Properties of Pellets Made from Sorghum Stalk, Corn Stover, wheat straw, and Big Bluestem. Industrial Crops and Products, 33, 325-332.

Torjai, L., Nagy, J. and Bai, A. 2015. Decision Hierarchy, Competitive Priorities and Indicators in Large-Scale ‘Herbaceous Biomass to Energy’ Supply Chains. Biomass and Bioenergy, 80, 321-329.

Tsai, H. F. and Luan, C. J. 2016. What makes firms embrace risk? A risk-taking capability perspective. Business Research Quarterly, 19, 219-231.

Tyndall, J. C., Berg, E. J., and Colletti, J. P. 2011. Corn stover as a biofuel feedstock in Iowa’s bio-economy: An Iowa farmer survey. Biomass and Bioenergy 35:1485-1495.

U.S. Department of Energy. 2016. 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 1: Economic Availability of Feedstocks. M. H. Langholtz, B. J. Stokes, and L. M. Eaton (Leads), ORNL/TM-2016/160. Oak Ridge National Laboratory, Oak Ridge, TN. DOI:10.2172/1271651

Verhofstadt, E. and Maertens, M. 2014. Smallholder cooperatives and agricultural performance in Rwanda: do organizational differences matter? Agricultural Economics, 45:39-52.

Vilko, J., Ritala, P. and Edelmann, J. 2014. On uncertainty in supply chain risk management. The International Journal of Logistics Management, 25:1, 3-19.

von Blottnitz, H., Curran, M.A. 2007. A review of assessments conducted on bioethanol as a transportation fuel from a net energy, greenhouse gas, and environmental life cycle perspective. Journal of Cleaner Production, 15:7, 607-619.

Wang, Y., Ebadian, M., Webb, E. and Sokhansanj, S. (2017-03, accepted). Impact of the biorefinery size on the logistics of corn stover supply. Applied Energy.

Weinstein, J. 2008. A postgenomic visual icon. Science, 319:1772-1773.

Weiser, C., Zeller, V., Reinicke, F., Wagner, B., Majer, S., Vetter, A. and Thraen, D. 2014. Integrated Assessment of Sustainable Cereal Straw Potential and Different Straw-Based Energy Applications in Germany. Applied Energy, 114, 749-762.

Wilkinson, L and Friendly, M. 2009. The history of the cluster heat map. The American Statistician, 63:2:179-184.

Xu, H. and Brown, D. G. 2017. Sensitivity of a stochastic land-cover change model to pixel versus polygonal land units. International Journal of Geographical Information Science, 31:4, 738-762, DOI: 10.1080/13658816.2016.1231316

Yue, D., You, F. and Snyder, S. W. 2014. Biomass-to-bioenergy and Biofuel Supply Chain Optimization: Overview, Key Issues and Challenges. Computers and Chemical Engineering, 66, 36-56.

Zhang, Z., Cui, X., Jeske, D. R. and Borneman, J. 2012. Biclustering scatter plots using data depth measures. Statistical Analysis and Data Mining, 102-115, DOI:10.1002/sam.11166

Zhang, F., Johnson, D. M. and Johnson, M. A. 2012. Development of a simulation model of biomass supply chain for biofuel production. Renew Energy, 44:380–91.

Zhou, Y., Yang, L., Xu, L. and Yu, B. 2016. Inseparable robust reward-risk optimization models with distribution uncertainty. Japan J. Indust. Appl. Math. 33:767-80. DOI:10.1007/s13160-016-0230-z

Zhang, J. F., Zhang, X., Li, C., Zhang, W. Y., Zhang, J. K., Zhang, R. H., Yuan, Q. P., Liu, G. Q. and Cheng, G. 2015. A comparative study of enzymatic hydrolysis and thermal degradation of corn stover: understanding biomass pretreatment. RSC Advances, 5:46: 36999-37005.

Appendix A. Figures and Tables

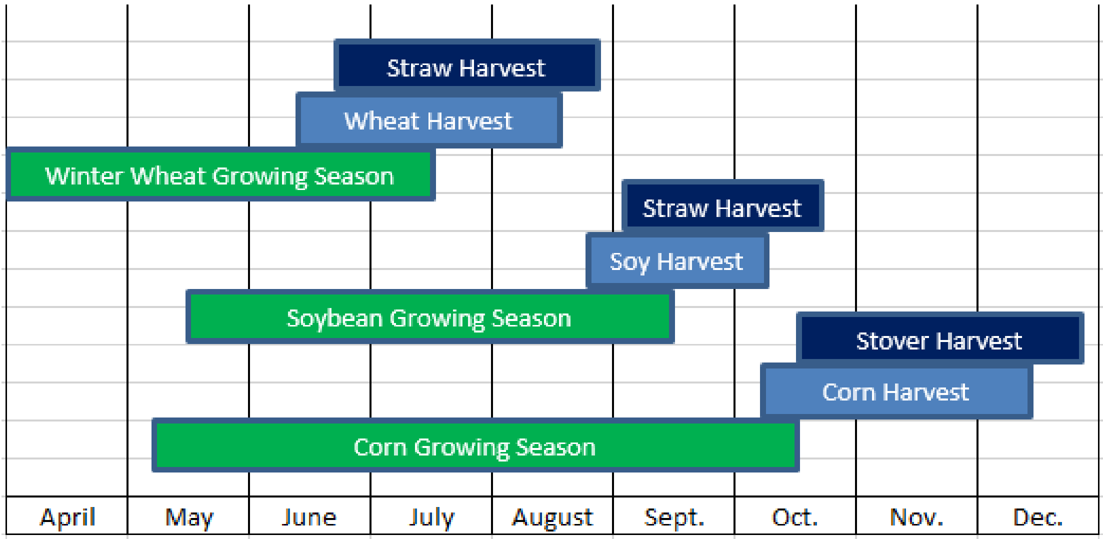


Figure A 1. Southern Ontario crops and residue harvesting Window (Marchand, 2015)

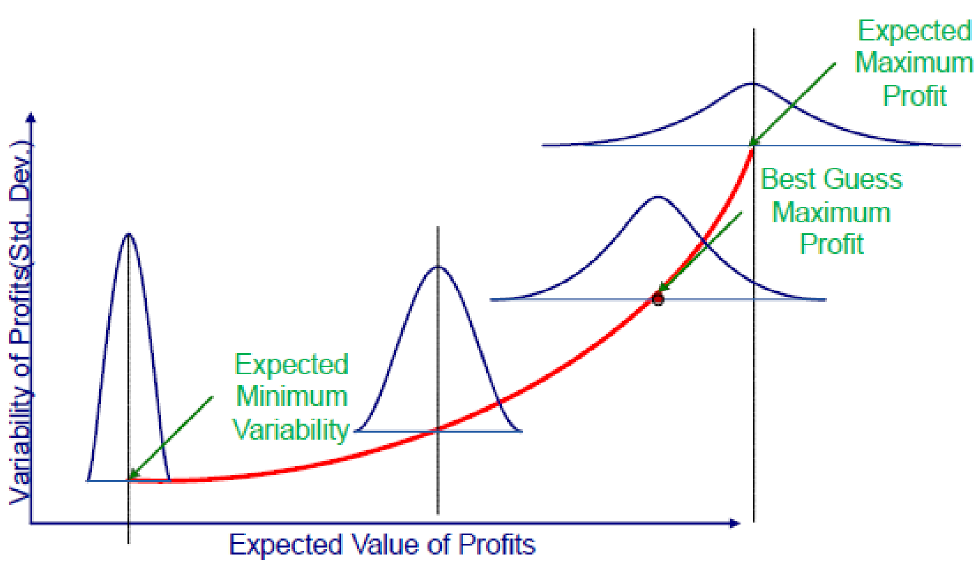
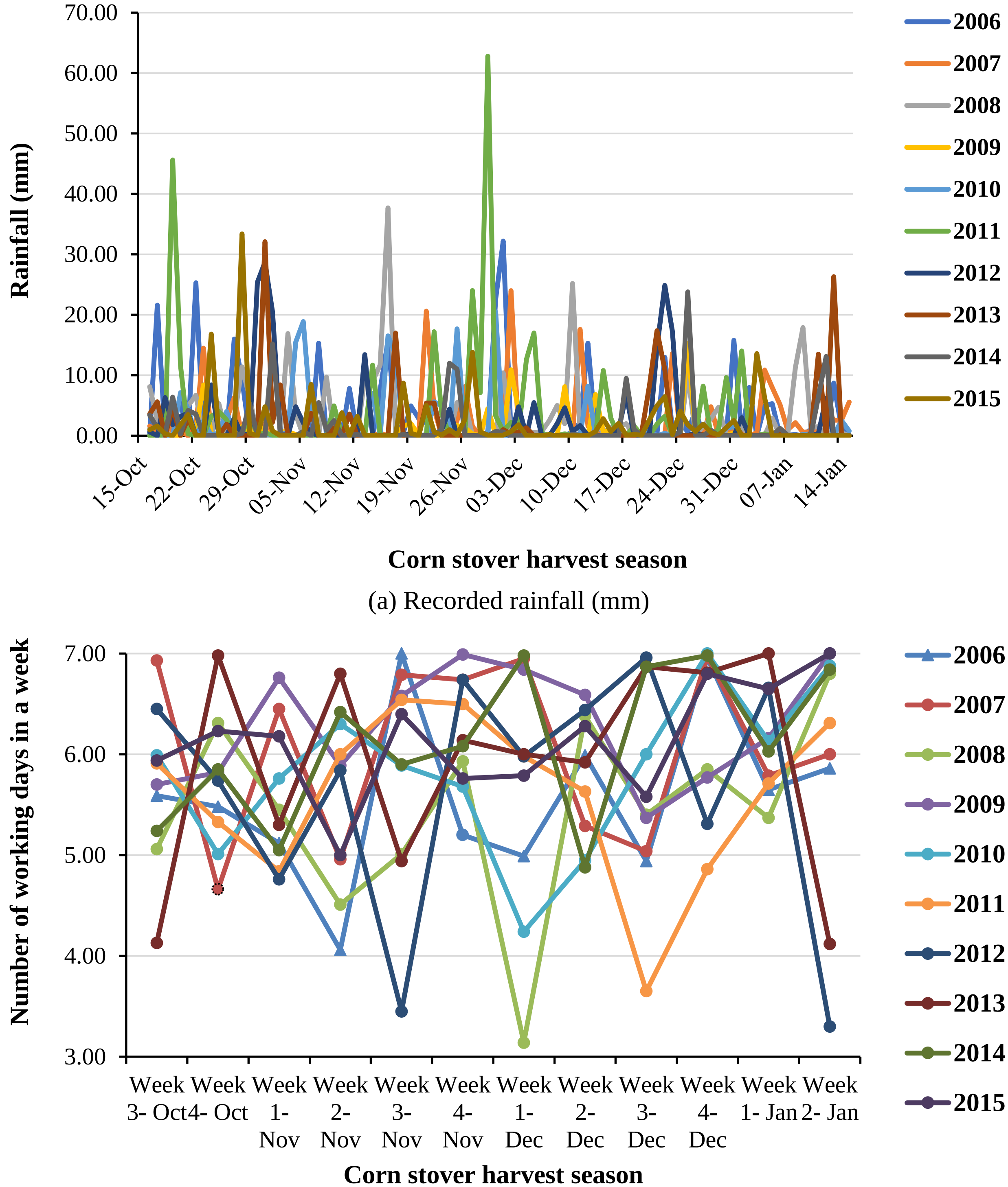


Figure A 2. Risk curve based on variability (adopted from Goetschalckx et al., 2012)



(a) Recorded rainfall (mm)

(b) Estimated number of working days in a week

Figure A 3. Amount of rainfall and the estimated working days during the corn stover harvest season in the period of 2006-2015

Table A 1. Literature review – various costs associated with the supply chain of crop residue ($/dt)

Crop Residue	Harvest and Packaging Field Machinery & Labour	Field-Side Storage	In-Field Transportation	Essential Nutrients Replacement	Farmer's Premium	Reference
Soybean Straw	22.05	4.00	5.50	28.30	N.A.	McDonald, 2010
Wheat Straw	22.05	4.00	5.50	26.32	N.A.	McDonald, 2010
Wheat Straw	9.63	2.29	4.25	22.62	5.50	Sultana et al., 2010
Corn Stover	28.80	N.A.	7.91	N.A.	11.02	Perlack & Turhollow, 2002
	16.60	8.94	7.21	N.A.	17.52	Hess et al., 2009
	25.24	N.A.	5.51	19.29	N.A.	Morey et al., 2010
	26.88	4.00	5.50	32.36	N.A.	McDonald, 2010
	36.30	N.A.	N.A.	18.60	N.A.	Hart & Edwards, 2012
	29.91	6.50	4.76	N.A.	N.A.	Oo et al., 2012
	28.53	N.A.	6.96	57.39	N.A.	Edwards, 2014

Table A 2. Average stover sugars and lignin concentration in central Iowa, USA (Karlen et al 2011)

	Glucan g/kg	Xylan g/kg	Galactan g/kg	Arabinan g/kg	Mannan g/kg	Lignin g/kg
Continuous Corn						
Upper Half	358	224	16.9	32.4	5.0	138
Lower Half	380	204	13.4	23.5	4.8	165
Whole Plant	364	223	16.6	31.5	5.2	144
Rotated Corn						
Upper Half	347	221	15.8	30.4	5.8	134
Lower Half	376	187	9.8	18.2	4.7	157
Whole Plant	355	214	14.9	27.5	4.9	144

Table A 3. Recommended sustainable corn stover removal rate (DuPont, 2015)

Grain Yield	Stover Production	Sustainable Stover Removal Rate	
		Continuous Corn	Corn-Soybean Rotation
bu/acre	dry tonne/acre	dry ton/acre	dry ton/acre
150	3.2	1.1	0.0
160	3.4	1.4	0.3
170	3.6	1.5	0.5
180	3.9	1.8	0.7
190	4.1	2.0	0.9
200	4.3	2.2	1.1
210	4.5	2.4	1.4
220	4.7	2.6	1.5
230	4.9	2.8	1.7
240	5.2	3.1	2.0
250	5.4	3.3	2.2

Table A 4. Stover available for harvest based on grain yield in Southern Ontario (Marchand, 2015)

Grain Yield	Total Stover	Stover Available for Harvest
bu/acre	dry tonne/acre	dry tonne/acre
150	3.22	1.14
160	3.43	1.27
170	3.65	1.40
180	3.86	1.53
190	4.08	1.66
200	4.29	1.78

Table A 5. Fixed and variable transportation cost coefficients

Transportation	Biomass	Fixed Cost	Unit	Variable Cost	Unit	Reference
Trucking	Straw	5.24	$/dt	0.123	$/dt/km	Mahmudi & Flynn, 2006
	Straw	5.45	$/wt	0.22	$/wt/km	Sultana et al., 2010
	Corn Stover	7.11	$/wt	0.146	$/wt/km	Ma & Eckhoff, 2012
	Miscanthus	6.3	$/wt	0.13	$/wt/km	Ma & Eckhoff, 2012
	N.A.	6.84	$/dt	0.1641	$/dt/km	Hamedani, 2015
	550 kg bale	3.4	$/wt	0.32	$/wt/km	Mupondwa et al., 2012
	pellets	3.84	$/wt	0.17	$/wt/km	Mupondwa et al., 2012
Railway	Straw	17.01	$/dt	0.0277	$/dt/km	Mahmudi & Flynn, 2006
Railway	N.A.	20.52	$/dt	0.0333	$/dt/km	Hamedani, 2015

Table A 6. Biorefinery and logistics data for IBSAL-MC simulation

Operating days in a year- bio-conversion facility*	340 days
On-site inventory at the bio-conversion facility*	three-weeks of stover supply
Average harvestable stover yield	1.72 dry tonnes/ac
Maximum transportation distance in the supply area	197 km
Distance between the intermediate storage site and the bio-conversion facility*	15 km
Storage dry matter loss in a year (%)	5-20
Bale size and bale bulk density	0.9×1.2×2.4 m; 9-12 lb/ft^3
Working hours in a day	10 hours
Percentage of the total time to mobilize logistics equipment between corn fields (unproductive time)	20%

** Personal communication with Bioindustrial Innovation Canada (BIC) Inc., November 20, 2015*

Table A 7. Equipment data* for IBSAL-MC simulation

Equipment	Flail Chopper	Baler	Bale collector	Loader	Tractor	53' flatbed trailer and truck
purchase price ($)	35,000	140,000	250,000	90,000	200,000	195,000
Useful life (year)	8	8	8	8	12	10
Power (kw)	-	-	240	90	135-165	335
Width (m)	6	6	-	-	-	-
Speed (kph)	5-12	6-12	24	-	-	66.16± 20.53 69.21±24.11
Efficiency (%)	0.7-0.85	0.7-0.85	0.7-0.9	0.5-0.8		0.8-0.95
Number of bales per load	-	-	12	3	-	39
Winding factor			1-1.2			1-2
Dry matter loss (%)	5	10	-	2	-	-

** Personal communication with AGCO Inc., April 24, 2016.*

Table A 8. Probabilities of the occurrence of the combination of sugar price and corn stover delivered costs at 30% farm participation rate

		Sugar market price range, $/tonne					
		225-275	275-325	325-375	375-42	425-475	475-525
Corn stover delivered cost range, $/dt	75-85	0.4%	0.7%	1.2%	1.9%	1.1%	0.5%
	85-95	3.5%	6.0%	11.2%	17.2%	10.3%	4.3%
	95-105	2.6%	4.5%	8.4%	13.0%	7.8%	3.2%
	105-115	0.2%	0.3%	0.5%	0.8%	0.5%	0.2%
	115-125	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table A 9. Probabilities of the occurrence of the consolidated combination of sugar price and corn stover delivered costs at 40% farm participation rate

		Sugar market price range, $/tonne					
		225-275	275-325	325-375	375-42	425-475	475-525
Corn stover delivered cost range, $/dt	75-85	0.8%	1.4%	2.6%	4.1%	2.4%	1.0%
	85-95	4.2%	7.3%	13.5%	20.8%	12.5%	5.2%
	95-105	1.6%	2.7%	5.0%	7.8%	4.7%	1.9%
	105-115	0.0%	0.1%	0.1%	0.2%	0.1%	0.0%
	115-125	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Table A 10. Probabilities of the occurrence of the consolidated combination of sugar price and corn stover delivered costs at 50% farm participation rate

		Sugar market price range, $/tonne					
		225-275	275-325	325-375	375-42	425-475	475-525
Corn stover delivered cost range, $/dt	75-85	1.1%	1.9%	3.5%	5.4%	3.3%	1.4%
	85-95	4.2%	7.4%	13.7%	21.1%	12.7%	5.3%
	95-105	1.2%	2.2%	4.0%	6.1%	3.7%	1.5%
	105-115	0.0%	0.0%	0.1%	0.1%	0.1%	0.0%
	115-125	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

Appendix B. Mathematical models applied in IBSAL-MC

IBSAL-MC utilizes Microsoft Excel to handle input and output data and ExtendSim software to construct and perform the simulation model as shown in Figure B1. The information management module aims to fulfill the daily feedstock demand, provide a smooth flow of biomass in the supply chain, avoid bottlenecks in the supply chain, utilize the equipment efficiently to reduce operating costs, and quickly react to any disturbance and shock in the supply chain to keep the system robust, while Three source of delay in the supply chain are considered - moisture content, weather condition and machine unavailability (Ebadian, 2013).

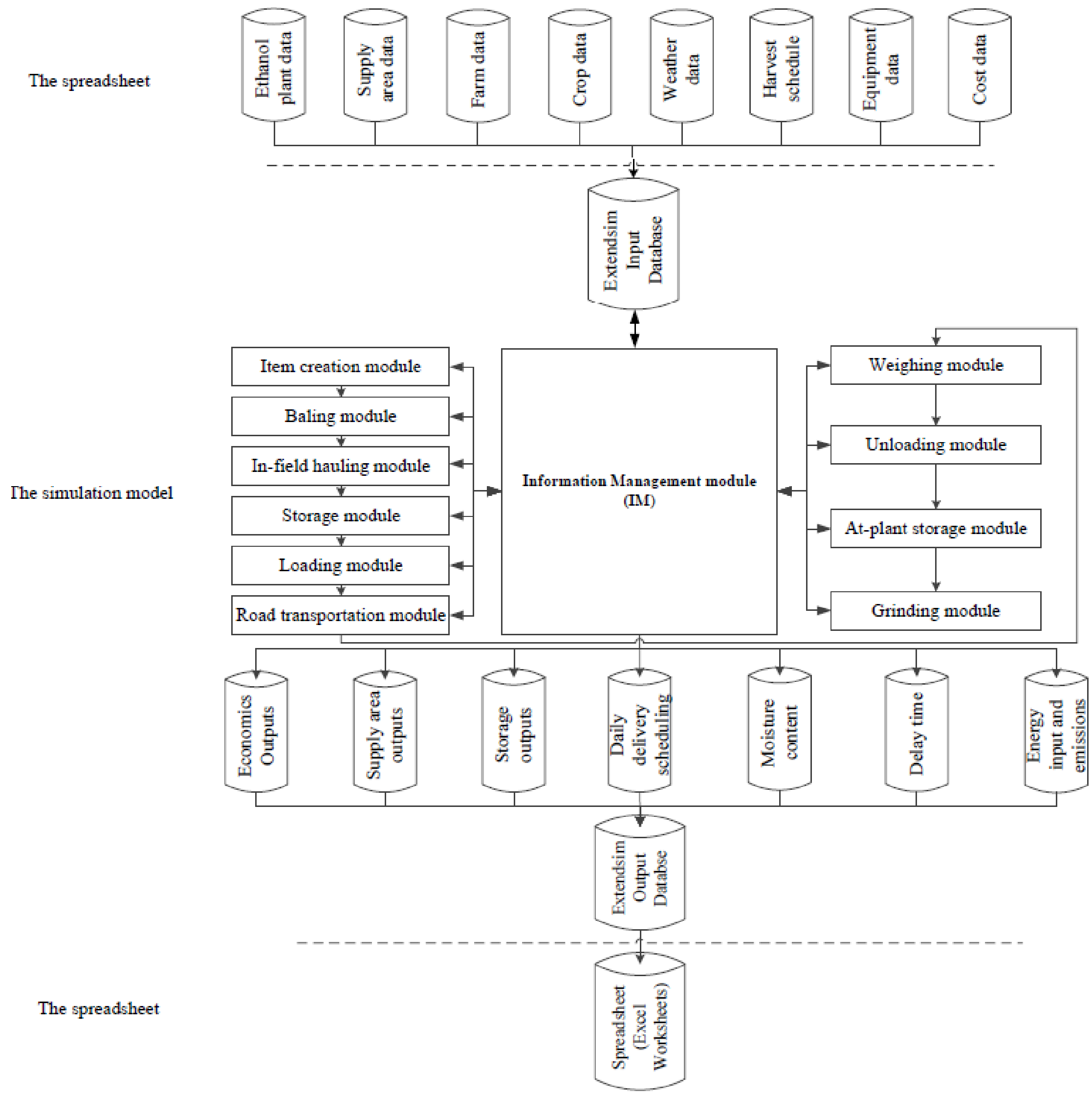


Figure B 1. Structure of the simulation model (adopted from Ebadian, 2013)

IBSAL-MC is governed by a set of mathematical equations each models one operation or governs one decision making process in the simulation. In this appendix, a few equations are selected to illustrate the how some operations are modeled.

The daily number of items (a unit of corn field) read for harvest is calculated according to the following equation:

$$H_i = N_{items}(P_i - P_{i-1}) \qquad \text{Eq. B1}$$

where H_i is the daily number of items ready for harvest, P_i is the cumulative harvested fraction on day i, P_{i-1} is the cumulative harvested fraction on day i – 1 and N_{items} is the total number of discrete items used in the model (Sokhansanj et al., 2006[b]).

For traveling field equipment, such as windrowers and balers, the performance depends on the width of the cut and the forward speed, thus, it is estimated by the following equation:

$$t = t_m + 8.25A/Swe \qquad \text{Eq. B2}$$

where A is harvest area (ac), S is the equipment's forward speed (mph), w is the cut width (ft), e is the equipment's efficiency (fraction decimal), t is the time required for the equipment to complete an operation (hr) and t_m is the time in field on operations besides traveling (hr) (Sokhansanj et al., 2006[b]).

For various operations involved in the simulation, the operation costs are calculated as the following (Ebadian, 2013):

- Baling:

$$Collection\ costs = Baling\ costs + Baling\ DML\ costs \qquad \text{Eq. B3}$$

$$Baling\ costs = Amount\ of\ baled\ biomass \times baling\ cost\ per\ tonne + number\ of\ bales \times twine\ cost\ per\ bale \qquad \text{Eq. B4}$$

$$Baling\ DML\ costs = Baling\ DML \times price\ of\ biomass \qquad \text{Eq. B5}$$

- In-field hauling:

$$In-field\ hauling\ costs = Loading\ costs + Transportation\ costs + Unloading\ costs + In-field\ handling\ DML\ cost \qquad \text{Eq. B6}$$

- Loading and unloading:

$$Loading\ and\ unloading\ costs = number\ of\ bales \times (loading\ time + unloading\ time) \times stinger\ cost\ per\ hour \qquad \text{Eq. B7}$$

$$In - field\ transportation\ costs = transportation\ time\ of\ a\ round\ trip \times number\ of\ trips \times stinger\ cost\ per\ hour \quad \text{Eq. B8}$$

$$In - field\ hauling\ DML\ cost = Hauling\ DML \times (price\ of\ biomass + baling\ cost + twine\ cost) \quad \text{Eq. B9}$$

- Storage:

$$Storage\ costs = storage\ estbalishment\ costs + Storage\ DML\ costs \quad \text{Eq. B10}$$

$$Storage\ establishment\ costs = storage\ capacity \times storage\ cost \quad \text{Eq. B11}$$

$$Storage\ DML\ costs = storage\ DML \times (price\ of\ biomass + baling\ cost + twine\ cost + in - field\ hauling\ cost) \quad \text{Eq. B12}$$

- Road transportation:

$$Road\ transportation\ costs = number\ of\ loads \times (loading\ time + unloading\ time) + truck\ cost\ per\ hour \times transportation\ time\ of\ a\ round\ trip \times number\ of\ trips \quad \text{Eq. B13}$$

$$Road\ transportation\ DML\ costs = transportation\ DML \times (price\ of\ biomass + baling\ cost + twine\ cost + in - field\ hauling\ cost + storage\ cost + loading\ cost) \quad \text{Eq. B14}$$