# A SYSTEM DYNAMICS APPROACH to COMPARATIVE ANALYSIS of BIOMASS SUPPLY CHAIN COORDINATION STRATEGIES

by

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## ABSTRACT

### A System Dynamics Approach to Comparative Analysis of Biomass Supply Chain Coordination Strategies

**Shohre Khoddami**

Biomass is one of the most efficient renewable energy sources to increase energy security and reduce the environmental issues. It could be utilised as back-up or main source of energy in off-grid remote northern communities of Canada, which are currently rely on fossil-fuels. However, small scale of energy demand, necessity of continuous energy supply, and spatial dispersion of such remote communities restrict the competitiveness and efficiency of bioenergy.

Managing bioenergy supply chain from supplying biomass to conversion facilities is vital to overcome the challenges in expanding bioenergy production. In this sense, forming collaboration among the entities plays a key role to improve the economy of scale and efficiency of bioenergy production. In the literature, several coordination strategies resulted in varying impacts on entities' profit or cost. As such, analyzing and comparing them in various conditions could assure selecting the most efficient one. This study recommends quantity discounts and cost-sharing coordination policies to promote the biomass level at communities in a cost-efficient manner through establishing bundling orders and benefiting the lower cost.

This dissertation employs a system dynamics approach to simulate coordination scenarios and make the optimal decisions in a biomass supply chain including suppliers, hubs, and end-user. On that basis, performing a comparative analysis under various conditions and assumptions provide insights into the impact of coordination and selecting the preferred choice of coordination strategy for each player. The simulation-based optimization model is applied to a bioenergy supply chain case study in Canada's off-grid northern communities. The results of this research point to a significant role of coordination in improving the cost efficiency as well as the level of biomass-based energy production.

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# Contribution of Authors

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# Chapter 1: Introduction

## 1.1. General Overview

Countries worldwide have been increasingly focusing on developing renewable and sustainable energy sources due to climate change concerns and environmental issues caused by greenhouse gas emissions from fossil fuels, which has become one of the most severe challenges in the 21st century. The need to address the world energy crisis, fossil fuel dependency, and achieving energy security has also encouraged use of renewable energy sources as an alternative option for fossil fuels [1]–[6]. Biomass is one of the main and abundant sources of renewable energy for both developed and developing countries. Biomass resources, including forestry, agricultural and municipal residues, and wastes, could be converted to various forms of energy, such as electricity, bio-fuel, and heating for homes and industrial facilities. In this regard, biomass has been recognized as an essential source of electricity generation because of high greenhouse emissions in combusting the fossil fuels to generate electricity [1], [2], [3], [4], [5], [6], [7], [8], [9], [10], [11], [12].

The use of biomass resources to meet the various forms of energy demand is widely considered a key means of greenhouse gas emission reductions, energy security, and social and economic improvements. Also, biomass contributes to rural development by supporting agriculture sectors through promoting employment opportunities and income generation [1], [12]. From the economic perspective, biomass conversion technologies relate to a lower levelized capital and operational cost than other renewable energy sources [13]. The Levelized Cost of Electricity (LCOE) is a fundamental economic metric used to compare the alternative methods of electricity generation regardless of unequal capital costs, operation costs, maintenance costs, useful life, etc. LCOE is "an average electricity price that must be earned by a specific generation source to break even" [14]. Besides, biomass resources could generate different types of energy with higher efficiency than energy production from wind and solar energy technologies [13].

Despite the fact that biomass resources are diverse and widespread across Canada and could be converted to electricity via many methods, biomass supplies a low percent of Canada's foremost energy demand [11]. However, it is predicted that collecting and processing unused biomass in fields and forests after the harvesting process could supply a considerable percentage of the energy, particularly for many off-grid remote communities, which are mainly relying on fossil fuels as the primary source of electricity production [11], [13]. Remote communities' dependency on fossil fuels limits their economic, environmental, and social improvements [13]. In this regard, Canadian federal government provides funding and supports to promote wood-based bioenergy projects for heat and power generation in such areas to reduce fossil fuel dependency as well as environmental and socio-economic developments [15],[16].

A biomass supply chain is the flow of biomass from the land to end-users and consists of five main elements, including harvesting and collecting biomass, pre-treatment, storage, transport, and energy conversion [2],[4]. The biomass supply chain has several peculiar characteristics: seasonality and uncertainties in biomass supply, diversity and dispersion of suppliers, low density of biomass, and demand variation. These distinctive features differentiate the biomass supply chain from the traditional supply chain [2]. Besides, biomass is an economically feasible energy source for large-scale energy production because it associates with high logistics costs. On the other hand, large-scale biomass production cause environmental issues such as loss of natural habitats, soil degradation, degradation of forests, and water pollution. Also, food criticism is another issue while using a large scale of biomass from food crops [2], [5]. In this sense, the use of biomass as a source of energy for remote communities comes with further challenges, including remoteness and spatial dispersion of communities as well as small economies of scale. Furthermore, remote communities in the north of Canada need a constant energy supply because of the harsh weather conditions in such areas. Due to these challenges in supplying biomass for energy generation in remote areas, efficient biomass supply chain management is imperative to enhance the profitability of electricity generation for remote northern communities of Canada [13].

SCM (Supply Chain Management) manages trade-offs between supply chain members such as suppliers, distributers, and customers. These parties are interrelated with financial, information, and product/service flows. Without an effective management, each member optimizes a part of the supply chain regardless of their decision's impact on the performance of total supply chain. In this sense coordination has a crucial role in SCM because it could coordinate and manage the decisions of individual parties and accordingly improve the supply chain performance. Coordination strategies manage the interdependencies among players' activities in various stages of the supply chain. Therefore, all involved players would reach a compromise and benefit from coordination [17], [18]. Indeed, “The main objective of supply chain coordination is to devise a mechanism that will induce the retailer to order the right quantity and set the right retail price so that the total profit of supply chain is maximized.” [17].

The peculiar attributes of the biomass supply chain need efficient management of biomass supply chain and logistics network to ensure the continuous supply of biomass while minimizing the total cost [19]. Besides, efficient biomass logistics is vital in providing sufficient biomass quantities to conversion facilities at a reasonable final price [20]. On the other hand, there are complex trade-offs between decisions in various stages of the biomass supply chain. Due to the interdependencies involved, the decisions could not be made independently, and each element of the network need to be managed considering the entire supply chain benefits [19]. Consequently, developing coordination strategies could play a key role in managing the trade-offs and improve biomass supply chain efficiency. One of the significant objectives of coordination strategies is to motivate involved players to align the order quantities from suppliers with demand at the end users while maximizing the profit or minimizing the total cost [17]. Several studies have developed incentive-based coordination strategies to promote green and biomass supply chain efficiency (e.g. [13], [21], [22], [23], [24], [25], [26], [27], [28])

In the light of the above facts, there are many complex decision problems in managing and optimizing the biomass supply chain activities [29]. Also, Coordination, which is imperative to effective supply chain management, is formed in a dynamic setting with feedback relationships among the coordinated parties [30], [31]. There are several mathematical and simulation approaches to model and optimize biomass supply chain systems [32]. Computer simulation models can model the complex systems and the behavior of a dynamic supply chain [32], [33]. Also, simulation-optimization models incorporate optimization methods with simulation approaches to find optimal solutions through running the simulation model [32]. The system dynamics (SD) approach is used as a simulation-optimization methodology to model the nonlinear behavior of the complex systems and obtain the optimal schedule of the decision variables over time, as well as finding the impact of the decisions on the behavior of the system [32], [34]. SD is a modeling approach developed by Forrester [35], capturing feedback loops and associates with the non-linearity, time-delay, and multi-loop configurations of complex and dynamic systems. Several studies applied the SD approach to simulate the coordination mechanisms and analyze their effects on the supply chain performance over a long time [31], [28], [36], [37], [38].

## 1.2. Problem Statement

Considering a typical biomass supply chain network, the biomass supply chain in this study includes suppliers, hubs as purchase-distribution channels, and remote communities as the end-users of electricity [13]. Due to the weather condition in remote northern areas of Canada, the electricity generation from biomass is considered an alternative for diesel in this study to ensure continuous electricity generation in these areas.

Dealing with the mentioned challenges in supplying biomass for power generation in Canada's remote communities requires an efficient biomass supply chain to ensure a sufficient supply of biomass at a reasonable price while minimizing the total cost of the supply chain. The vast majority of studies have established coordination strategies to improve supply chain efficiency. Moreover, comparison analysis of the coordination strategies to select the most cost-efficient one with the highest biomass-based electricity generation could play a significant role in promoting the biomass supply chain performance for these communities and overcoming the relevant challenges. In this regard, this study coordinates the biomass supply chain for Canada's remote northern communities by establishing quantity discounts and cost-sharing coordination strategies. The coordination strategies are then compared by investigating the impacts of strategies on the biomass supply chain characteristics over time in various conditions. In this sense, several decisions need to be made over time under each coordination scenario while having complex relations and feedback. Using the SD approach, we simulate the coordination scenarios in remote communities' biomass supply chain and obtain optimal decision schedules. We then analyze the impacts of coordination strategies on cost efficiency and bioenergy production to compare the coordination scenarios in different conditions. On that basis, the decision on the choice of coordination strategies or no coordination scenario is made.

## 1.3. Research Objective

The main goal of this study is to investigate and compare the coordination strategies to enhance the cost efficiency in supplying biomass to remote communities and the level of bioenergy production in such areas, where a focus is on biomass supply for electricity generation in off-grid remote areas. The analysis is based on minimizing the total collective cost of the supply chain with respect to specific constraints and assumptions. In this sense, quantity discounts and cost-sharing coordination strategies are established to encourage bundled ordering and accordingly improve the economy of scale as well as bioenergy production. On the basis of total supply chain cost minimization, the impact of coordination scenarios on the overall cost of players, the cost performance of the biomass supply chain, and the biomass supplied to the communities are analyzed and compared. This overall goal is achieved by developing a simulation-optimization approach to investigate the optimal supply chain characteristics under each coordination scenario. The system dynamics approach is a platform to simulate coordination scenarios and accordingly optimize the supply chain's performance under each scenario. In this regard, there are four main research questions to address in this study:

1. Conduct and run simulation models to integrate the quantity discounts and cost-sharing coordination scenarios in the biomass supply chain for remote communities. The stock-flow diagrams with the mathematical formulations under each coordination scenario are developed. A real case study in remote northern areas of Canada is applied to the models with the time horizon of "t" to show the applicability of the proposed models and analyze the results of the models.
2. Develop and solve the simulation-based optimization model over the time horizon. The optimal schedule of decision variables and the behavior of the system under each coordination scenario are obtained.
3. Compare the coordination strategies to identify the players' preference in the choice of coordination strategies or no coordination strategy. The comparison analysis is done considering the case study results on the cost efficiency gained and the level of bioenergy production under each scenario.

4. Conduct the comprehensive comparison analysis by analyzing the case study outcomes' sensitivity to changes in the model parameters. At this stage, the players' preferred strategy changes are investigated under different conditions and assumptions.

## 1.4. Thesis Outline

In addition to the current chapter, this study contains the following chapters:

Chapter 2 reviews the literature related to biomass and bioenergy supply chain management. In addition, coordination strategies used for coordinating supply chains are studied while particular attention is advocated on the biomass supply chain and supply chains with small demands. Also, the studies that used simulation-optimization models in managing the supply chain and, in particular, in coordinating the supply chains are reviewed in this chapter.

In chapter 3, the system dynamics models are developed to simulate the coordination scenarios, to find the relevant optimal supply chain decisions, and to explore the comparative analysis of biomass supply chain coordination strategies in remote communities considering the case of Canada's remote northern communities. The models are applied to the case study in section 3.4. The results and the sensitivity of the outcomes are presented and analyzed in this section.

Finally, Chapter 4 summarizes this study, including the conclusions, novelty of the study, limitations, and some suggestions for future research.

# Chapter 2: Literature Review

## 2.1. Chapter Overview

Biomass is an efficient energy source that could generate electricity, particularly in off-grid northern communities of Canada. However, peculiar attributes of biomass and challenges of supplying biomass to these areas need to be addressed. In this sense, supply chain coordination could overcome the challenges to ensure cost-efficient and reliable bioenergy generation. In this regard, a simulation-optimization model simulates the coordination scenarios and makes optimal complex decisions over time. In this chapter, the biomass-based energy production chain is described, and then the significant challenges that should be addressed, particularly in remote areas, are defined. The supply chain coordination strategies that have been used in supply chains with similar features to the biomass supply chain are then reviewed. Finally, a review on system dynamics modeling and its application in supply chain management and coordination is performed.

## 2.2. Biomass and Bioenergy Supply Chain Management

### 2.2.1. Biomass and Bioenergy

There has been increasing attention to using renewable energies rather than traditional types to achieve economic, environmental, and social benefits. The main reasons are carbon mitigation, energy security, and the availability of renewable sources. Biomass is one of the primary sources of renewable energies, which stems from forestay and agriculture residues as well as manure and bio-wastes. Biomass resources can be converted into various types of energy for residential and industrial purposes, such as heat, electricity, biofuel, and/or a combination of them [2], [39], [40], [41].

Interest in biomass has been recently growing due to the fact that biomass energy generation is associated with several environmental, social, and economic advantages. The main advantages and motivations in using biomass are as follows [2], [39], [42], [43], [44], [45]:

- Simple and effective storage with flexibility in transportation and usage in various energy sectors

- The unstable trend of oil and fossil fuel price
- Greenhouse gas (GHG) emission mitigation
- Fossil fuel dependency reduction (energy security)
- Improving the rural economy by creating new job opportunities, decreasing rural immigration, growing farmers' income,
- Low-priced heat supply and lower levelized cost of electricity[1] (LCOE)
- Incentive policies for improving the investment in renewable energy production such as feed-in-tariff policy for biomass-based electricity generation in Europe

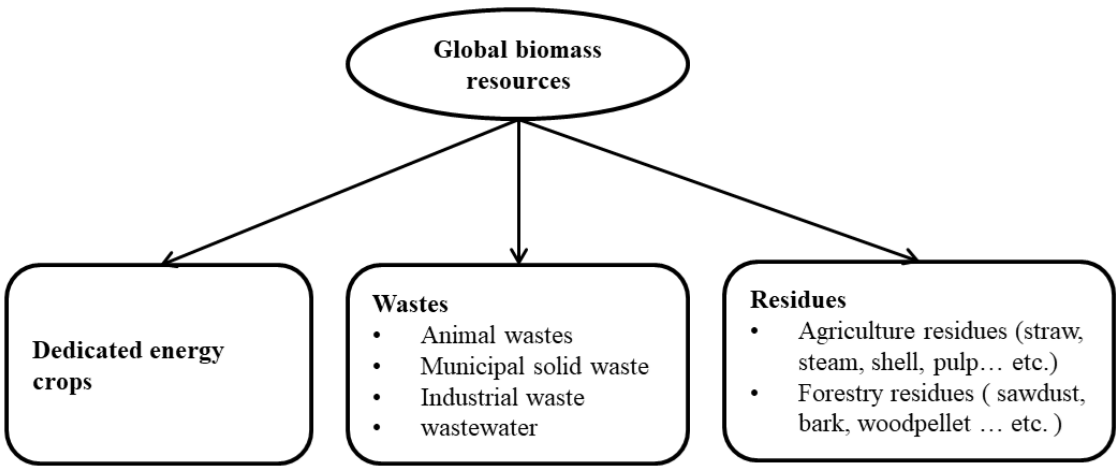


Figure 1-Biomass resources categories- adapted with modification from [46].

Biomass resources are categorized as dedicated energy crops, wastes, and residues (Figure 1). The crops that are grown and produced for energy purposes are defined as non-food energy crops. Energy crops have been an attractive and efficient biomass source since they can produce high yields and a high amount of energy with little inputs. Wastes are also utilized as biomass sources and include animal wastes, municipal solid waste, industrial wastes, and wastewater, which are defined as "waste of all types of used water from residential, industrial, business, and agriculture areas." Other frequently used types of biomass are residues containing agriculture and forestry residues. Agriculture or crop residues are the portions of plants not fitted to be eaten, and leftovers remain on-farm areas after harvesting activities and crop processing. Straw, stem,

[1] Levelized cost of electricity (LCOE) is defined as "an average electricity price that must be earned by a specific generation source to break even" [14].

stalk, leaves, husk shell, pulp, stubble are some kinds of agriculture residues obtained from cereals (such as rice, wheat, corn, etc.), cacao, tea, fruits, etc.  [46]. Forestry residues are "the total mass of the wood (including the above and below ground of the wood), bark, branches, and leaves of woody shrubs and trees." [44]. Forest-based residues are classified into three categories: "(1) residues from the harvest and extraction of logs, (2) residues during timber manufacturing, plywood, and so on, and (3) waste wood products from transport pallets, construction timber, and furniture". The significant forestry kinds of residues are bark, sawdust, and wood pellet. [46].

Forrest-based biomass and mainly wood processing residues are the most important sources for generating bioenergy, biofuel, and biomaterials [43], [44]. Since Canada is among the top five countries with the most considerable forest resources, wood processing residues are the most common bioenergy sources in Canada. The potential benefits of wood biomass include waste reduction, landfill and wildlife habitat saving, diminishing the threat of fire and acid rain, promoting income and job opportunities in rural and forestry communities, conversion technology improvement [43], [44].

Wood pellets are defined as "a densified form of biomass usually made from by-products of primary wood processing facilities"  [47]. Despite the fact that pellets are more expensive than other forms of wood biomass such as wood chips or round wood, they have been recognized as a popular and largest traded source to generate bioenergy recently [43]. This is due to the wood pellets' advantages, such as easier storage, handling, and transportation compared to other forms of biomass because of the uniformity of pellets' size, high-density level, and low moisture content. These benefits make pellets an efficient source of bioenergy that could be transported and utilized in remote areas [43], [48], [49], [47]. In this sense, Canada is among the major producers and exporters of wood pellets [48], [49].

### 2.2.2. Biomass Supply Chain Network

The supply chain is a network of people, activities, and processes to produce and deliver finished products or services from suppliers to end-users. It includes suppliers, storage facilities, distributors, manufacturers, and end-users [19], [44]. A biomass-based energy production chain consists of three main interdependent groups of operations (Figure 2). The upstream supply chain comprises the activities from producing biomass to delivering to a conversion facility, while the downstream supply chain covers the operations from the conversion process to the bioenergy consumption site. The operations related to the conversion process also set up the midstream supply chain [19], [5]. In this sense, the main entities in BSC (biomass supply chain) include biomass supply site, biomass pre-treatment and storage, biomass to energy conversion, and demand site. Biomass supply site [19]. As shown in Figure 2, the processes in BSC are interrelated, and decisions in each stage will affect the other processes [5].

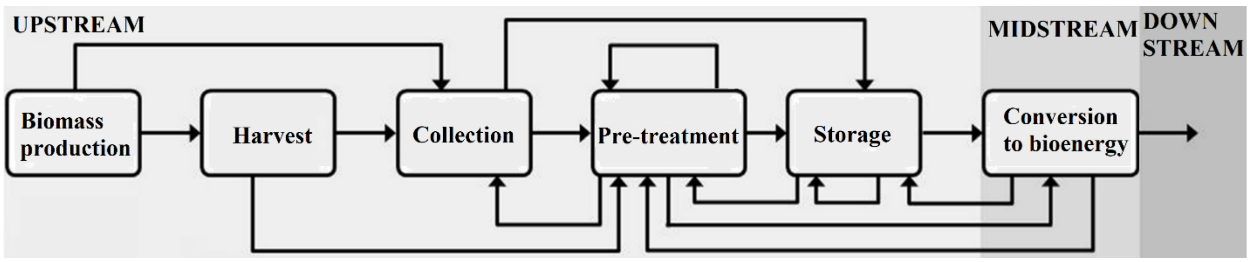


Figure 2- The flow of operations in a biomass to bioenergy production chain [5].

The processes at each stage are explained as follows:

1. Biomass production, Harvesting, and collection

At the first stage, all biomass types need to be cultivated, harvested, and collected. However, the plantation site establishment needs for dedicated energy crops plantation at the first step. Agriculture residues are collected after harvesting the agriculture yields. On the other hand, The cutting trees need to be left at the harvesting location to produce forestry residues before employing the pre-treatment operations to diminish the moisture content [19], [5]. Freshly harvested and collected biomass could be stored or undergo a pre-treatment process before being stored [19].

The main decisions at this stage associate with land allocation, harvest scheduling, biomass collection planning by considering bioenergy demand, weather conditions, and land availability [2] ,[19].

2. Biomass pre-treatment

Subsequently, thermal, mechanical, and chemical pre-treatment processes are employed to increase the energy content as well as reduce the unit size and moisture level of biomass. Consequently, biomass feedstock quality is improved with handling, storage, and transportation processes being performed easily. Most Frequent pre-treatment activities are chipping/grinding, drying, torrefaction, carbonization, pelletization, chopping, and shredding [2], [19], [44]. It should be noted that the pre-treatment process is not necessary for all biomass materials. For instance, logs need to maintain a specific amount of moisture content to be qualified for pelleting [2], [19].

3. Biomass storage

Due to the seasonal availability of most biomass types and the requirement of continuous bioenergy supply at the end-user site, on the other hand, biomass storage is essential to ensure the biomass supply has matched the demand [44], [50]. Biomass storage could be located at the biomass source site, next to the conversion plants, or at an intermediate point at some hubs between biomass supply sites [19], [44], [50]. Biomass storage at the end-user site as a safety stock needs to prevent the potential disruption of the feedstock supply [50]. There are various types of biomass storage, such as covered storage and hypethral or open-air storage, which has limited or no protection from weather conditions [19], [50]. On-field storage with limited protection needs few logistical requirements, and it allows biomass moisture reduction by natural drying [50]. In this sense, open-air storage might be selected for biomass types with high moisture content, such as forest residues, while covered storages are preferred for dried biomass types [44]. However, it is impossible to store biomass on the field without protection for a long time because it may cause biomass deterioration [19], [50]. In this regard, the storage type could be selected considering several factors, including the biomass type, the shape and size of biomass, biomass quantity needs to be stored, weather condition, required biomass quality, storage duration, and location, transportation distance, bioenergy type, available resources such as space and capital. A complete biomass supply chain needs an arrangement of different storage types in real cases [50]. Due to the trade-offs between storage and transportation cost, the typical decisions at this stage, such as the location of storage sites, the storage capacity, and scheduling, need to be optimally made [2], [19].

4. <u>Biomass transportation</u>

Transportation and logistics is a significant and costly phase that affects the biomass supply chain cost and efficiency significantly [19], [44]. Biomass transportation modes include roads, railways, waterways, pipelines, and the combination of two or more types. A mode of transportation is selected considering the available transportation infrastructure and distance as well as biomass and bio-product form [19]. In this phase, the decisions on type, capacity, and transportation schedules are made to ensure the cost and time-effective biomass supply chain [2], [19].

5. <u>Biomass conversion</u>

Biomass feedstock can be converted to several forms of energy, including electrical energy, thermal energy, and energy carriers/ biofuels, through a wide range of conversion technologies and processes. The main conversion technologies are classified as thermochemical and biochemical processes [51]. The decision-makers deal with making optimal decisions on conversion planning, location, and technology of conversion facility [2], [19].

### 2.2.3. Challenges in Biomass Supply Chain Management

Biomass supply chain contains peculiar characteristics that make it more vulnerable and differentiate it from the typical supply chain. The major features and issues are fluctuations in biomass supply quantity, quality, and lead time due to seasonality of biomass, weather conditions instability, soil quality variability, pests and diseases, perishability of biomass. On the other hand, a steady bioenergy supply is required at the end-user site. Therefore it is necessary to consider issues and uncertainties. In this sense, there are several uncertainties in the biomass supply chain, including (1) biomass demand and price, (2) biomass supply, (3) technology and processes, (4) government policies, (6) transportation and logistics processes, and (7) natural uncertainties such as flood, hurricane, earthquake, etc., which have a low chance of occurrence [52]. Mafakheri and Nasiri [2] also categorized the issues and challenges in the biomass supply chain into (1) technical, (2) financial, (3) social, (4) environmental, (5) policy and regulatory, and (6) institutional issues.

1. <u>Technical issues</u>

Utilizing biomass with a replacement planting of biomass resources is a significant challenge that needs to be considered in an efficient biomass supply chain to prevent biomass shortage. There is also concern regarding the inefficiency of biomass-based production technologies since the conversion technologies are young and immature. In this sense, proper inventory policy, holding safety stock, lead time increase with customers' agreements, effective maintenance techniques, and outsourcing options could overcome the technological issues [2], [52]

2. Financial and economic issues

High capital costs of biomass-based energy production necessitate decreasing the operational costs considering all steps of the biomass supply chain. Other financial challenges are uncertainties in the rate of returns and unstable biomass market prices. Also, the scale of biomass production and delivery, location, and size of conversion facilities affect the supply chain cost. [2].

3. Social issues

Biomass-based production system has both positive and negative social impacts. Positive impacts such as job creation and rural development have been discussed previously. However, social acceptance of biomass-based production is affected by negative issues such as change of land use for biomass production, crop modification, indirect influence on food security and food price, as well as loss of biodiversity [53].

4. Environmental issues

The main environmental issues of biomass supply chain are; greenhouse emission because of transportation and logistics activities, loss of biodiversity and natural habitats, soil degradation, degradation of forests, water use level, and water pollution [2], [53].

5. Policy and regulatory issues

There are direct incentives and indirect supports such as fossil fuel tax to encourage bioenergy production, mainly in the transportation sector and feed-in-tariff policy in the electricity sector in Europe. However, the extra cost leads to increasing the cost of transportation in the biomass supply chain. In this sense, currently available supports need to be replaced by encouraging a more sustainable biomass-based production system [2].

6. Organizational and institutional issues

Lack of supply chain standards and different organizational cultures among biomass supply chain echelons leads to coordination issues among parties. In addition, efficient change management and response plans must adapt to changes and uncertainties in the biomass supply chain [2].

It should be mentioned that remote communities associate with additional issues in producing biomass-based energy such as remoteness, geographical dispersion, small economies of scale, and tough weather conditions. [13].

Biomass supply chain management plays a critical role in handling the challenges mentioned earlier and uncertainties to promote biomass supply chain efficiency [5]. Supply chain management is defined as "planning and management of all activities involved in sourcing and procurement, conversion, and all logistics management activities" [5]. It focuses on coordinating all parties, processes, and information flows to meet end-user demand on time with the aim of minimizing the overall cost of the supply chain. In this regard, biomass supply chain management aims to minimize overall costs, including production, logistics, harvesting, storage, conversion, and other processes, while ensuring a steady supply of biomass at a reasonable price with the minimum environmental impacts [2], [41]. In this sense, biomass supply chain efficiency is affected by the coordination level among the BSC parties, which is a challenging issue due to the complex interdependent relations among the parties [41], [44]. As such, various optimal decisions at different stages could not be made independently [19].

## 2.3. Supply Chain Coordination

There are flows of information, product, and service, as well as financial flows among supply chain members. Effective management of these flows requires coordination among the players' activities with the aim of aligning each player's decisions with the supply chain objectives [18].

Brian Fugate et al.[18], presented the benefits of supply chain coordination, including risk reduction, cost improvement, higher profits, inventory reduction, and increasing supply chain efficiency. They classified the coordination approaches into decentralized and centralized decision-making mechanisms. The centralized decision-making approach (single-person perspective) considers a single-decision-maker to make optimal decisions in a system. On the other hand, the supply chain members cooperate and coordinate their activities to optimize the decentralized decision-making approach (team-based approach). This approach has been used extensively in practice than the other two approaches.

### 2.3.1. Supply Chain Coordination Mechanisms

Brian Fugate et al.[18] categorized the coordination strategies into the price, non-price, and flow coordination (Figure 3) [18].

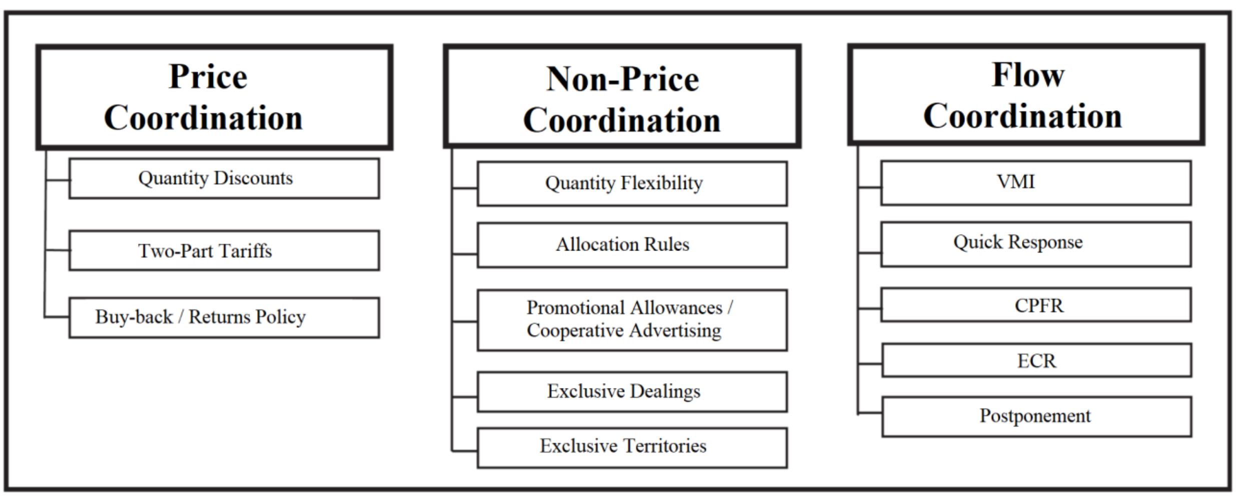


Figure 3- Coordination mechanisms classification [18]

Channel coordination could be established by a contract as a set of rules such as a price or quantity discount, return policies, etc., between the involved parties in coordination [33]. Some studies have a different categorization considering the contract approach as one category (Figure 4) [18],[54]. On that basis, revenue/cost/benefit-sharing mechanisms have been widely used in supply chain coordination.

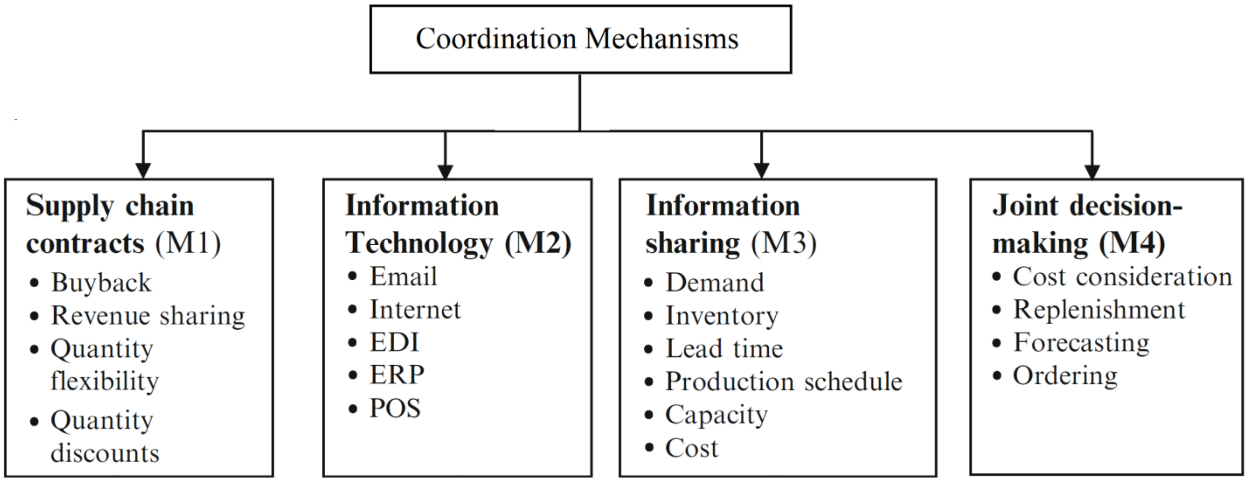


Figure 4- Coordination mechanisms categories [54]

This research classifies the reviewed coordination studies considering the coordination mechanisms' categories by Brian Fugate et al.[18]. Also, the studies that coordinate the supply chain through revenue/cost/benefit sharing are reviewed and presented in section 2.1.1.3.

#### 2.3.1.1. Price Coordination Mechanisms

The most frequent price coordination mechanism is offering quantity discounts to encourage collective order quantities [18]. T. Boyacı and G. Gallego indicated the lot sizing and pricing decisions need to be coordinated, particularly in a supply chain with small demands and multiple geographically dispersed retailers [55]. In this sense, the quantity discount mechanism induces the buyer to increase the order size and benefit from the discounted price offered by the supplier to compensate for increased storage costs. As such, discount quantities encourage bundling of orders [56], [57]. In a comprehensive literature review, S.P. Sarmah et al. [57] reviewed and classified the papers have been used quantity discounts to coordinate supply chain subject to deterministic environment into four categories: (1) "supplier's perspective coordination models", which coordinate the lot size and offered discounted price with the aim of the supplier's profit maximization ; (2) "buyer and supplier perspective coordination models", which coordinate order quantity with respect to total supply chain's cost minimization; (3) "buyer and supplier coordination models" under game-theoretic framework, which coordinate the supply chain through quantity discount under non-cooperative (each player aims at maximizing his profit or minimizing his cost) and cooperative games (the objective is total supply chains' cost minimization or total supply chains' profit maximization); (4) "single supplier and multiple buyers coordination models", which could consider any of the previous objectives to coordinate the supply chain. The results pointed to the effectiveness of quantity discount coordination models in improving the supply chain performance and savings in the system. In this regard, quantity discounts could coordinate the pricing, ordering, and inventory policies and ultimately lead to joint profit maximization of supplier and buyer [58]. This could obtain the best price discrimination and encourage the increasing quantity per order considering the total demand [59].

Presenting a simulation model, D. SIRIASy and S. MEHRA [60] compared quantity discounts and lead time-based discounts, which are two incentive-based coordination mechanisms. The quantity discount in the proposed model encourages the distributer to increase the inventory level and benefit from the offered discount from the manufacturer. Under the lead time scenario, the distributor could benefit from the discount by offering a higher lead time to the manufacturer. The simulation results pointed to the significant impact of discount mechanisms on the supply chain member's profit [60]. Although quantity discount might not be the best coordination strategy in supply chains with stochastic demand [60], it is developed in the supply chain with probabilistic demand as well, such as the study by Jianli Li and Liwen Liu [61]. They coordinated the supply chain consisting of a supplier and a buyer considering the probabilistic demand. The proposed model determined a certain quantity discount based on joint decisions and divided it between the buyer and the supplier. The results illustrated the improvement of both members' profit as well as entire supply chain performance.

Several studies propose discounts to coordinate the timing of orders, price, and inventory policies to promote cost savings and supply chain efficiency. In a supply chain consisting of a manufacturer, who outsources the products, and multiple retailers with steady demand, T.D. KLASTORIN et al. [62] recommended price discounts to coordinate the order cycle of the retailers and the manufacturer. The manufacturer motivates the retailers to order at specific times and benefit from the reduced purchase price in the proposed channel coordination. Consequently, the manufacturer could reduce the storage costs, and supply chain efficiency is promoted. Chintapalli et al. [63] proposed integration of minimum advance-order quantity and advance-order discounts to encourage on-time orders and benefit from the discounts. According to the study, offering advance-order discounts could not coordinate the supply chain. The proposed combined contract coordinated the supply chain by offering the advance-order discount subject to minimum order quantity.

Buyback and two-part tariff contracts are the other strategies coordinating the quantity and pricing decisions by encouraging the buyer to order more [33], [18]. Buyback contracts are a frequently used strategy in the Fashion industry [54]. According to the buyback or return policy, the buyer or a downstream partner would be able to return any portion or a full of the initial order and get the refund or credit from an upstream partner subject to an agreement [33], [18], [54]. Harish Krishnan et al. [64] have indicated that the integration of buyback and cost-sharing agreements among retailers and suppliers leads to coordinating the supply chain. In a two-part tariff contract, a supplier offers a wholesale price and a fixed fee to a buyer, and the buyer then decides on purchase quantity considering internal cost, the offered price, and the fixed fee in the contract [33], [18]. Qingguo Bai et al. [65] have analyzed a two-part tariff contract in a two-echelon supply chain with time-varying demand affected by price, level of sustainability, and promotional effort by the manufacturer. The proposed model results in perfect coordination.

Price coordination mechanisms have also been used in the context of the green supply chain. For instance, Basiri and Heydari [66] developed a green channel coordination model in a supply chain with two players, a retailer, and a manufacturer. They studied the sale of a green product that is supposed to be sold beside the non-green product considering the demand of both products as a function of quality, retailer's sales efforts, and retail price. In this regard, they modeled and compared three decision scenarios, including decentralized decision making, integrated scenario, and collaboration model. The results showed that the establishment of a collaboration model leads to more customers' satisfaction because of decreasing the retail price and generating a greener channel [66].

#### 2.3.1.2. Non Price Coordination Mechanisms

Brian Fugate et al. [18] categorized non-price coordination mechanisms to quantity flexibility contracts, allocation rules, promotional allowances, cooperative advertising, and exclusive dealings/territories, of which quantity flexibility contracts and allocation rules are the most frequent ones. There is flexibility in altering the order quantity by buyers based on quantity flexibility contracts. This could be established through several contracts, including minimum purchase quantity contracts, backup agreements, and special contracts. In minimum purchase quantity contracts, the buyer commits to purchase a minimum quantity with the flexibility to adjust the order quantity according to accurate demand information. Backup agreements provide the buyer's flexibility to purchase more quantity than the preliminary order quantity. Special contracts would also determine the terms of commitments for the buyer to purchase a minimum quantity and for the suppliers to deliver up to a certain quantity in case of having exceeding demand than the initial amounts [33], [18], [54]. It is observed that more flexibility leads to higher inventory costs, so inventory management needs to be considered in managing flexibility [54]. In this sense, F. T. S. CHAN and H. K. CHAN have developed a quantity flexibility contract for inventory management in a distributed supply chain with demand uncertainty. The results showed an effective reduction in system cost, retailer cost, supplier cost, inventory cost, and fill rate [67].

#### 2.3.1.3. Revenue/Cost/Benefit Sharing Contracts

One of the most frequent coordination mechanisms that have been used vastly is revenue/cost-sharing, which is an incentive-based contract. In this mechanism, the overall extra revenue/cost acquired through the coordination is shared among the involved parties in coordination [33].

Revenue sharing contracts could effectively coordinate the purchase quantity decision when demand is not affected by retailer effort [68]. In two-stage supply chains, the retailer could benefit from discounted prices by sharing a portion of his revenue with the manufacturer. RS contracts have also been used in a three-stage supply chain. Giannoccaro and Pontrandolfo [69] presented a two-contract model based on the revenue sharing strategy to coordinate a three-stage supply chain. Using the contract parameters, they increased the system efficiency and improved the beneficiary of all the supply chain players. They could establish channel coordination using two types of revenue-sharing contracts that allow the players to select optimal order quantities.

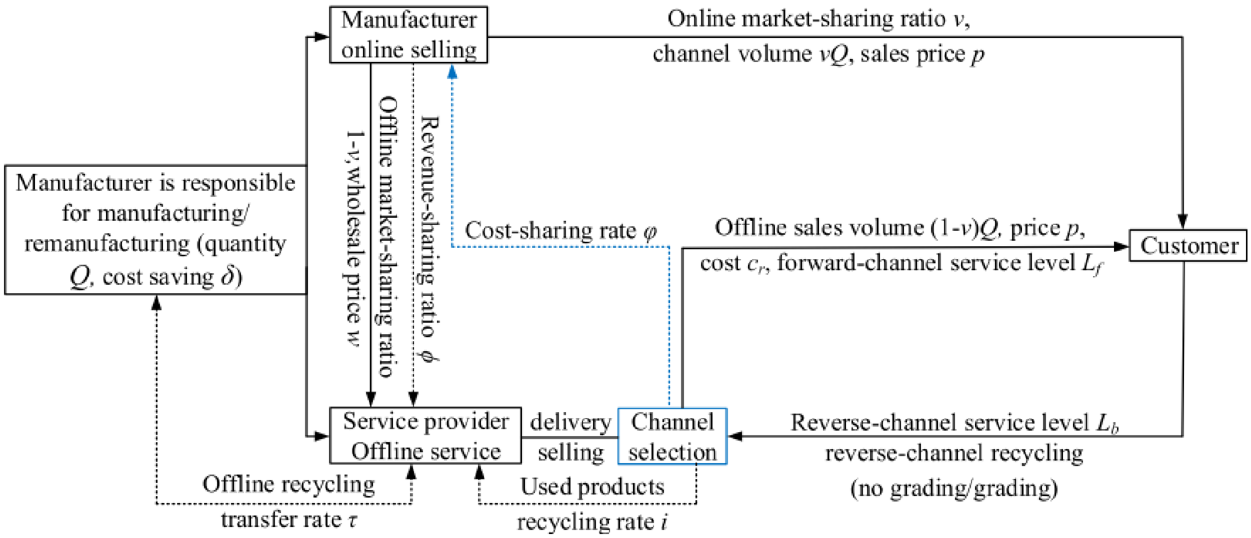


Figure 5- Incorporating revenue-cost sharing contract in a closed-loop dual-channel supply chain [70].

Revenue sharing contracts have been widely proposed in reverse supply chains [31]. Jiaping Xie et al. [70] coordinated a dual-channel closed-loop supply chain (CLSC) under the integration of cost-sharing and revenue-sharing contracts to promote the retailer's efforts to sell and recycle the products. As described in Figure 5, the manufacturer absorbs a portion of the retailer’s costs to encourage recycling used products and shares their revenue with the retailer to motivate them to promote the sales volume. The proposed model resulted in the higher profit of supply chain members.

Several studies have coordinated the supply chain under cost-sharing contracts. In this sense, a proposed cost-sharing mechanism by Frascatore and Mahmoodi [71] coordinated a supply chain consisting of a buyer and a supplier to avoid supply shortages and promote supply chain efficiency. In their model, the supplier is encouraged to create a higher supply capacity by sharing a portion of the capacity cost with the buyer. On the other hand, the buyer compensates the supplier by refunding a portion of the supplier’s payment to ensure both firms’ profit maximization. Debabrata Ghosh and Janat Shah [72] modeled a cost-sharing contract in the context of a green supply chain with two players, a manufacturer and a retailer. The proposed model incentivized the manufacturer to increase the greening level of the product by sharing greening costs with the retailer. The coordination among players through cost-sharing contracts leads to higher greening levels as well as promoting supply chains and firms’ profit [72]. The

Logistics cost-sharing strategy is also proposed in a fresh-product supply chain to increase logistics service level and compensate the cost of logistic service provider [73].

Integrating revenue sharing and cost sharing have been also attractive contracts to establish coordination among the supply chain players. In this regard, Hongfu Huang et al. [74] developed revenue sharing and cost sharing contracts to coordinate the supply chain consisting of unreliable supplier and a retailer with deteriorating products. The cooperative reliability investment contract motivates suppliers to invest in reliable production technologies and share a part of investment's costs, in return a portion of their revenue is shared with retailers. The proposed model leads to a higher players' profit through coordinating the production reliability and order quantity. Qingguo Bai et al. [65] studied a two stage supply chain for deteriorating items considering a manufacturer and a retailer with time-varying demand. They coordinated the supply chain using revenue and promotional cost-sharing (RPS) and two-part tariff contracts to promote the profit and reduce the carbon emission. In RPS contract, the manufacturer invested in sustainable technologies and reduced the wholesale price to encourage the retailer in promotional efforts and sharing a ratio of selling revenue with them. The retailer also shared a ratio of the promoting costs with manufacturer. In a TPT contract, the manufacturer motivated the retailer to cooperate by charging a lower wholesale price and a fixed cost as well as investing in sustainable technologies. The coordination results have caused to a higher profit with lower carbon emissions[65]. Incorporating revenue-sharing contracts with cost-sharing has also been utilized to coordinate a supply chain of wind equipment with multiple manufacturers and customers with the aim of promoting equipment availability [75].

#### 2.3.1.4. Flow Coordination Mechanisms

Flow coordination mechanisms manage and coordinate information flows such as demand, orders, inventory, etc., by sharing such information among the supply chain players [54]. The frequent mechanisms of this category are Vendor Managed Inventory (VMI), Quick Response (QR), Collaborative Planning, Forecasting and Replenishment (CPFR), Efficient Consumer Response (ECR), and postponement [18]. Information technology such as ERP (enterprise resource planning) and EDI helps rapidly exchange information and link supply chain operations from the initial point to the endpoint [54]. Information sharing leads to "bullwhip effect" reduction, system performance improvement, inventory level reduction, and cost savings for supply chain members [76]. Information sharing is also suggested to be combined with other coordination strategies to manage uncertainty and promote the supply chain performance under uncertainty [77].

### 2.3.2. Biomass Supply Chain Coordination

There are several barriers to develop bioenergy systems. Analyzing six case studies with different biomass resources, conversion technologies, and bioenergy type, K. McCormick and T. Kaberger investigated the success factors and potentials in bioenergy development. There are several obstacles in different stages, including farmers' hesitations in energy crops planting, financial feasibility problems in expanding bioenergy, lack of incentive regulations in renewable energy development, and lack of cooperation among different sectors [78]. Therefore, an organized biomass supply chain is vital to implement successful bioenergy systems. They concluded that forming collaboration among several sectors such as energy companies, biomass suppliers, local government, residents, etc., could successfully manage bioenergy expansion.

Several studies have focused on investigating various coordination incentive mechanisms among biomass supply chain members. Juanjuan et al. [22] established coordination between a farmer, a broker, and a biomass power plant under government incentives to share the alliance profit and define incentives for increasing the biomass supply quantity and electricity produced in biomass power plant (Figure 6). In this regard, three scenarios, including farmer-broker cooperative game, broker-biomass power plant cooperative game, and no cooperative game, have been modeled and compared. The results indicated that players' profit and biomass supply quantity are higher in coordination models than in no coordination models.

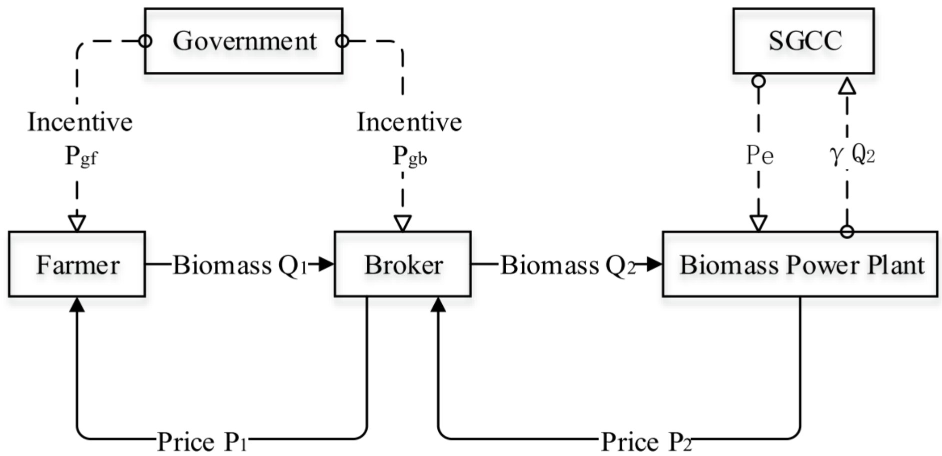


Figure 6- Power generation supply chain coordination under government incentive. SGCC: State Grid Corporation of China [22]

By designing an appropriate incentive mechanism under risk perception, Wang et al. [21] proposed three scenarios to coordinate the biomass supply chain (Figure 7). In the benchmark scenario, government incentive is not provided to farmers or middleman. Scenario 2 and 3 provide government incentives for farmers and middlemen subject to each member's profit maximization, respectively. The biomass purchase price is affected by risk perception level as well as a provided incentive. Subsequently, the biomass supply quantity is positively affected by the offered price. The model decides on a portion of the government's incentives to farmers, middlemen, and biomass power plants to address biomass collection difficulties and increase the yield from the farmers.

Integrating quantity discounts and cost-sharing mechanisms with the incorporation of biomass storage hubs, Mafakheri et al. [13] encouraged bundled biomass order quantities to overcome the challenges such as small economy of scale in supplying biomass to remote communities in the north of Canada and encouraging communities. As a result, the electricity production from biomass has been improved in remote communities. Another study proposed side payments to coordinate the biomass supply chain in these remote areas using game theory [79].

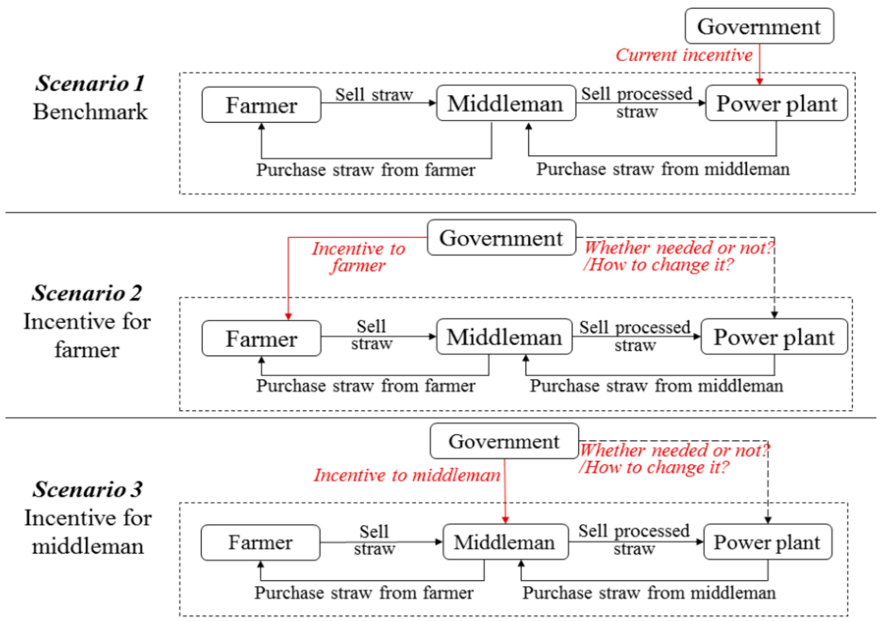


Figure 7- The structure of biomass supply chain coordination under different incentive scenarios [21]

To ensure a sustainable biomass supply, Li and Yang [24] designed over-production and under-production coordination contracts by providing incentives or penalties. An overproduction risk-sharing contract encouraged the biofuel producers to order additional quantities and benefit from a discounted price, while the farmers pay penalties in an under-production risk-sharing contract for shortage in biomass supply.

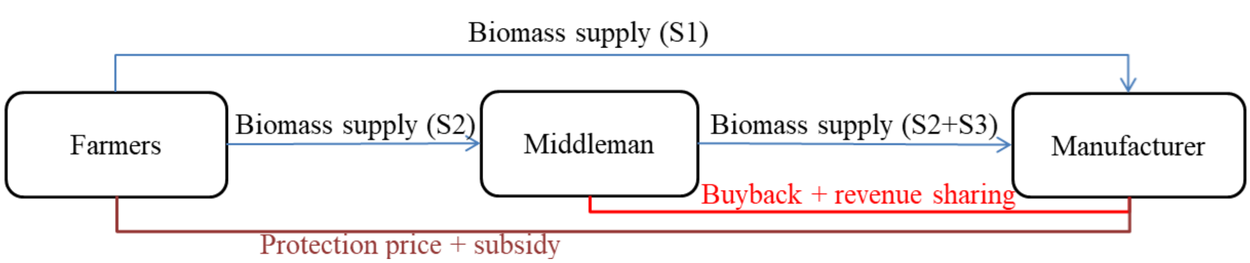


Figure 8- Two stage biomass supply chain contract coordination- adapted with modification from [27]

K. Fan et al. [27] modeled two coordination contracts in a solid fuel biomass supply chain containing multiple farmers, a middleman, and a manufacturer to promote the members' profit and biomass energy development (Figure 8). The model coordinated the manufacturer and middleman under revenue sharing with buy-back contracts considering stochastic demand. In this contract, the manufacturer purchased the excessive quantity and shared a portion of sales revenue with the middleman. The coordination established between manufacturer and farmer by providing a price subsidy and protective market price for farmers to ensure their profit when the purchase price could not make a profit or cover the supply cost [27].

## 2.4. System Dynamics Modeling

System dynamics is a method to model and analyze the dynamic behavior of complex systems over time based on feedback concepts of control theory. SD modeling considers non-linearity, time-lag, and multi-loop features to understand the behavior of complex and dynamic systems. Forrester first established SD [35] and provides a basis for computer models to analyze the structure and interactions of complex systems [80].

Forrester also presents a six-step system dynamics modeling, which illustrates in Figure 9 [81].

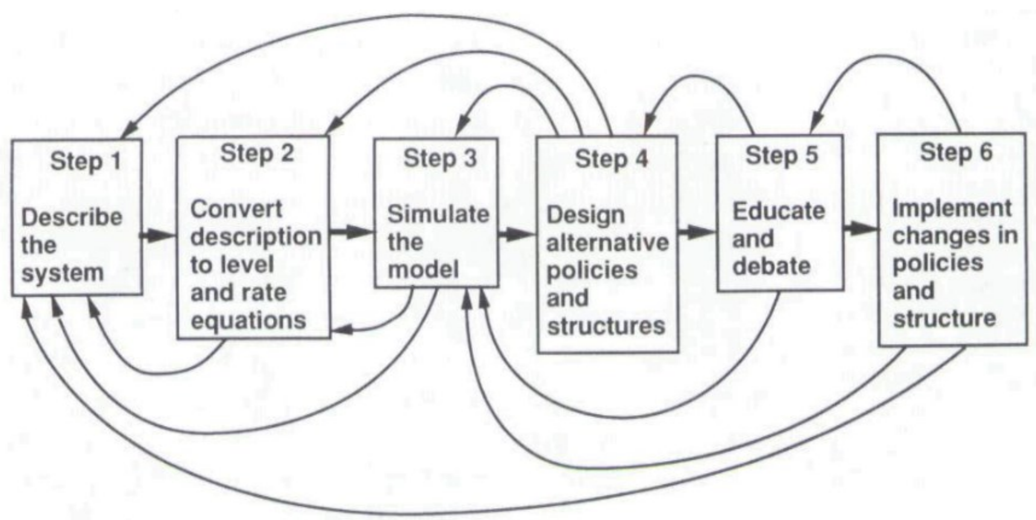


Figure 9-System dynamics modeling process [81]

On that basis, the steps of SD modeling consisting of the following steps: “(1) Identify the problem, (2) Develop a dynamic hypothesis explaining the cause of the problem, (3) Create a basic structure of a causal graph, (4) Augment the causal graph with more information, (5) Convert the augmented causal graph to a system dynamics flow graph, (6) Translate a system dynamics flow graph into STELLA or VENSIM programs or equations” [80]. The details of developing the SD model are provided as follows.

<u>Step 1- Developing the problem identification:</u> The problem needs to be understood clearly at the first stage of SD modeling. In this regard, the scope of the system, the problem’s causes, the key

variables, the policies to address the problem, and the change of the system's behavior as historical behavior (reference mode behavior) over a time horizon have to be defined. Five items need to be defined at this step, including: "(1) Definition of the problem, (2) Purpose of the model, (3) Systems approach, (4) Reference mode, (5) Time horizon" [80].

Step 2- Developing the dynamic hypothesis identification. The second step is to develop a conceptual model consisting of the critical feedback loops that could generate the reference mode behavior over time. This step includes the following steps: "(1) Endogenous feedback structure, (2) Observed and simulated reference mode behavior, (3) Theory to explain the reference mode behavior" [80].

Step 3- Developing casual loop diagram: The next step is defining the relationship and interdependencies among the variables (endogenous and exogenous) and developing causal loop diagrams (CLDs) to represent the feedback structures [80]. CLDs represent the concept of the model using cause and effect interactions. It contains the variables connected by causal links, which is illustrated by positive or negative link. A positive link means that cause and effect variables are positively related, and a negative link indicates that the increase in cause leads to the effects' reduction. The main feedback loops are labeled as reinforcing (positive) and balancing (negative) loops denoting by "+" and "-", respectively [81]. Developing CLDs consists of five steps: "(1) Define the problem and the objectives, (2) Identify the most important elements of the systems, (3) Identify the important secondary elements of the systems, (4) Identify the important tertiary elements of the systems, (5) Define the cause-effect relationships" [80].

Step 4- Building stock-flow diagram: Despite the fact that causal loop diagrams are well suited to represent the concept of systems by feedback structures, it has several limitations, such as failure to consider stock and flow structure. Stock and flows, besides feedback, are the two principal components of system dynamics modeling. Stocks give the state of the system to make decisions and are changed by the inflows and outflows [80], [82]. Moreover, stock-flow diagram (Figure 10) consists of several constant variables as well as auxiliary variables, which are the function of stocks and constants.

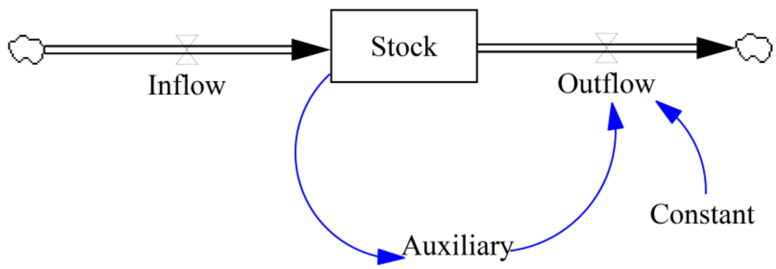


Figure 10- Stock-flow diagram adapted with modification from [82].

Developing the stock-flow diagram consists of the following steps: "(1) Define the problem and the objectives, (2) Identify the most important variables of the systems, (3) Identify the important secondary variables of the systems, (4) Identify the important tertiary variable of the systems, (5) Identify the variables representing the stocks, i.e., accumulations, (6) Identify the variables representing the flows having a unit of per unit time of the stock, (7) Ensure the inflows entering the stock and outflow leaving the stock" [80].

Subsequently, the relevant equations of stock-flow diagram are defined in Vensime or Stella programs. Finally, model validation and sensitivity analysis need to be performed to build confidence in the SD model [80].

### 2.4.1. System Dynamics Modeling in Supply Chain Management

System dynamics has been extensively used as a decision support model in the supply chain context [83]. Angerhofer and Angelides classified SD modeling in the supply chain management studies into "theory building, problem-solving and improving the modeling approach" [84]. Theory building studies aim to understand the system, problem-solving studies deal with addressing the supply chain issues, and the studies aiming to improve the SD modeling methodology in supply chain management are grouped as modeling approach improvement [84]. SD can be applied to several aspects of supply chain management (SCM) such as "International supply chain management (ISCM), Inventory management, Participate business modeling, Supply chain design, Demand amplification, Information visibility, Decision making in stock management, Supply chain reengineering, Integrated system dynamics approach" [85]. However, supply chain integration, information sharing, bull-whip effect, and inventory planning are among the supply chain issues often modeled by the SD approach [83]. Bala et al. [86]

developed system dynamics to model and analyze the complex rice supply chain in Bangladesh. Due to climate change impacts on supply and uncertainties, an efficient rice supply chain needs to be responsive to supply and demand variations timely and cost-effectively to ensure rice availability to customers in an optimal manner. In this regard, their proposed model investigated the sensitivity of supply, demand, and lead time variations on the supply chain performance, and different policy options have been analyzed to develop an efficient and cost-effective model [86].

SD also could be employed in various aspects of Green supply chain management (GSCM) similar to SCM aspects mentioned earlier [87]. Besides, SD is a strong method to model the complex causal relationships and dynamic behavior of sustainable supply chains [88]. T. Rebs et al. presented a research review on SD application in the context of sustainable supply chain management (SSCM). They have suggested a structure for SD modeling in the field of SSCM (Figure 11). The interdependencies among the economic, social, and ecological systems result in complicated feedback loops with time delays. These features make the system a complex dynamic one, which could be modeled by SD method to support decision-making in SSCM [88].

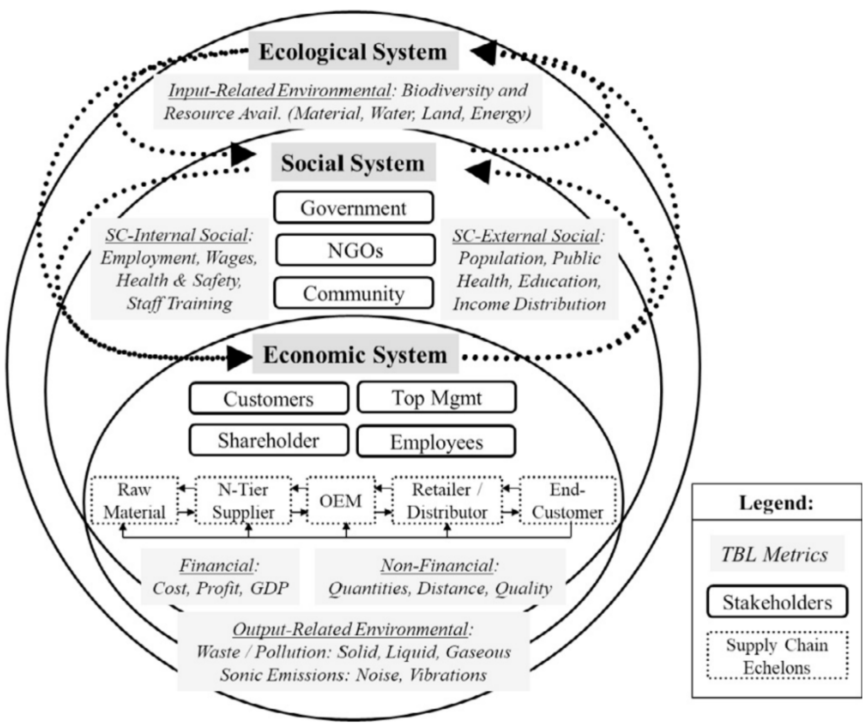


Figure 11- Framework for a systems thinking in the context of sustainable supply chain management [88].

SD has also been considered a powerful method to efficiently support decision-making in the energy sector's complex system [89], [90]. A research review by Saavedra et al. illustrated the extensive application of SD approach in decision-making processes in renewable energy supply chains such as bioenergy. This approach enables modeling and analysis of complex relationships among different sectors of renewable supply chain considering feedback loops and delays. Also, “what-if analysis” through SD simulation approach allows to understand the dynamic behavior of energy system under several scenarios and supports sensitivity analysis to evaluate the impact of new process establishment into the system [90]. Azadeh and Arani presented a hybrid system dynamics-mathematical decision-making model to simulate the biomass to biodiesel supply chain and obtain the optimal solutions. Due to the limitations on available water resources, land (biomass sources), and technology, there are several complex feedback relationships among parameters in a biodiesel supply chain. In this regard, SD has been used to model the complex biomass supply chain [91]. Incorporating heat incentive mechanism into biomass-based energy supply chain for non-residential buildings in the United Kingdome, Nasiri et al. developed a simulation-optimization model using system dynamics. The model captured the feedback among the “supply chain loop” and “asset management loop” as shown in Figure 12. Using SD, they could obtain the optimal schedule of decisions on biomass and backup boiler energy generation, biomass purchase order, and storage subject to various constraints with the aim of minimizing the system’s whole life cost [34].

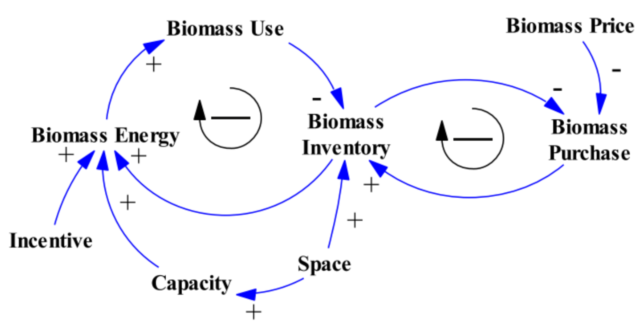


Figure 12- Asset management and supply chain causal loops in biomass supply chain [34].

### 2.4.2. System Dynamics Modeling in Supply Chain Coordination

Due to the fact that flexibility and fast response are vital in supply chain management, coordination could play a critical role and deals with the complexity [33]. Hing K. Chan and

Felix T.S. Chan [33] studied and classified the supply chain coordination mechanisms and reviewed the analytical and simulation approaches used to model, analyze and coordinate several decisions in the supply chain. This research review indicated that developing an analytical-based simulation model provides robust analytical solutions with quick responses to changes.

Tama et al. modeled three coordination scenarios, including coordination between farmer and distributer (scenario 1), distributer- wholesaler coordination (scenario 2), and coordination among farmer, distributor, and wholesaler (scenario 3) in a vegetable supply chain using system dynamics. They have analyzed the long-term coordination impacts on players' profit and supply chain in all scenarios through SD modeling. The comparison results showed that coordination among all players resulted in the highest profit of the supply chain [28]. Rendón-Sagardi et al. developed an SD modeling to simulate the coordination between production and procurement stages of an ethanol supply chain. SD simulation modeling has analyzed the effects of coordination policies on inventory and demand satisfaction [38].

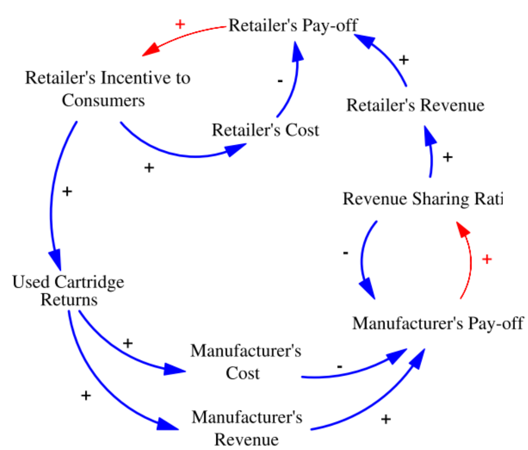


Figure 13- Causal loop diagram of revenue sharing incorporation into used ink cartridge reverse supply chain [30].

Mafakheri and Nasiri used system dynamics to model revenue sharing strategy in the reverse supply chain of used printer cartridges considering a manufacturer and a retailer. The developed causal loop diagram clearly shows the revenue sharing concept in reverse logistics (Figure 13). The decision problem has been formulated based on the developed model to provide optimal solutions for involved parties in coordination. The proposed model could have formulated the feedback relationships among the retailer's incentive strategy and manufacturer's revenue-sharing policy. The model also captured the complexity of the reverse supply chain since the used products vary in quality and quantity [31].

Integrating information-sharing mechanism into a three-stage supply chain consisting of a manufacturer, a distributor, and retailer by developing SD, Yong Feng made comparative analysis with the results of no coordination scenario over a long time. The retailer shared the market sales and demand information with the distributor and the manufacturer in the coordination scenario. The information-sharing effects on the supply chain have been analyzed by comparing the impact of market demand change on the players' order and inventory before and after information sharing over a long time. The SD simulation results illustrated that the supply chain behavior reaches a higher stability level after coordination [36]. Information sharing is also incorporated into a four-stage supply chain through SD modeling to analyze the dynamic coordination impact on customer satisfaction over a long time [37]. Another study by Bowon and Chulsoon modeled the VMI (Vendor-managed inventory) mechanism to coordinate the retailer and supplier decisions in a three-stage supply chain through the SD simulation approach [30]. Employing SD simulation approach, Ovalle and Marquez compared the impact of three coordination mechanisms, including VMI, CP (Collaborative Planning), and CF (Collaborative Forecasting), on the supply chain performance over a long time [92].

# Chapter 3: A System Dynamics Approach to Comparative Analysis of Biomass Supply Chain Coordination Strategies[2]

## 3.1. Introduction

Renewable energy production has been rapidly attracting attention in recent years to reduce fossil energy dependency and address environmental issues. One of the abundant renewable energy sources is biomass, which could be converted to different forms of energy, including electricity, bio-fuel, and heating for homes and industrial facilities. Biomass sources include plant, animal manure, and forestry and wood processing residues [1], [2], [9], [11], [93], [94]. Biomass conversion technologies are established with a lower levelized capital and operational cost compared to other renewable energy sources [13]. The Levelized Cost of Electricity (LCOE) is a useful economic scale to compare the various electricity generation technologies with different capital costs, operation costs, maintenance costs, useful life, etc. LCOE is "an average electricity price that must be earned by a specific generation source to break even" [14]. Also, biomass-based energy production efficiency is higher than that of wind and solar energy technologies [13]. The availability of different biomass types across Canada makes it an efficient source of energy to generate electricity, and a means of energy security for off-grid remote communities, which mostly rely on fossil fuels as the main source of energy [13]. Remote communities' dependency on fossil fuels restricts their potentials to promote economic, environmental, and social conditions. Canadian federal government funding has supported wood-based bioenergy projects for heat and power generation in remote communities to reduce the fossil fuel dependency in these areas as well as the development of clean energy systems, economic growth, and job creation [15], [95].

Despite all these benefits above, supply of biomass comes with several challenges such as seasonality, constraints on steady biomass supply, and diversity and dispersion of suppliers [2],[19]. Besides, there are further challenges for supplying biomass to the remote communities as a main or back-up source of electricity generation. The challenges include remoteness and

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[2] A version of chapter 3 has been published. [Shohre Khoddami], Mafakheri. F. and Zeng. Y. (2021) Energies 2021, 14, 2808. https://doi.org/10.3390/en14102808

spatial dispersion of communities as well as small economies of scale. In addition, in case of northern communities, there is the necessity of continuous (sometimes year around) energy supply because of the tough weather conditions [13]. These peculiar attributes require an efficient biomass supply chain management. In this sense, one of the main objectives in managing biomass supply chains is cost minimization while ensuring continuous biomass supply [19]. Besides, providing sufficient biomass quantities at a reasonable final price would be essential to biomass logistics [20]. The efficiency of biomass supply chains and logistic networks depend on various decisions in various stages of this chain and involve complex trade-offs [19]. In this sense, coordination could improve biomass supply chain efficiency. Supply chain coordination aims at developing a strategy to encourage involved parties to align the order quantities from suppliers of biomass with demand at the end users to ensure maximization of profit or minimization of total cost [33].

Several studies have focused on investigating various coordination incentive mechanisms among biomass supply chain members. Juanjuan et al. [22] studied the formation of alliance between a farmer, a broker, and a biomass power plant, in order to distribute the profit and adjust government incentives for increasing the feedstock supply quantity and biomass power plant's operation. By designing an appropriate incentive mechanism under risk perception, Wang et al. [21] proposed a mechanism to provide a portion of local government's incentives to farmers, distributors, and biomass power plant to address biomass collection difficulties increasing the yield from the farmers. To resolve the challenges in supplying biomass to remote communities in the north of Canada and encouraging communities to establish larger biomass order quantities, Mafakheri et al. [13] proposed to integrate quantity discounts and cost-sharing mechanisms with the incorporation of biomass storage hubs. Li and Yang [24] designed over-production and under-production coordination contracts to ensure a sustainable level of biomass supply to biofuel producers by providing incentives or penalties for participating farmers. With an overproduction risk-sharing contract, the biofuel producers benefit from a discount price for buying extra quantities. In an under-production risk sharing contract, the farmers pay penalties for under delivery of biomass quantities. To ensure on-time orders, Chintapalli et al. [63] offered a minimum advance-order quantity promoted by a combination of in-advance order discounts. Frascatore and Mahmoodi [71] recommended a cost-sharing mechanism to prevent supply shortage and promote supply chain efficiency in a supply chain consisting of a buyer and a seller. In their model, the seller initiates the supply capacity subject to a cost sharing among both players to ensure profit maximization. Another study proposed integrating revenue-sharing contracts with cost-sharing to improve coordination in case of a supply chain of wind equipment manufacturers and customer enterprises to promote equipment availability [75]. The cost-sharing strategy is also proposed in case of fresh-product supply chains [73].

System dynamics models have been proposed for simulating the behavior of complex systems and their associated decision-making procedures. Forrester first developed system dynamics (SD) methodology [35] as a modeling approach to incorporating feedback structures and dealing with the non-linearity, time-delay, and multi-loop structures of the complex and dynamic systems. SD has become a foundation for computer models to analyze complex systems' structure, interactions, and behavior [80]. A research review by Angerhofer and Angelides categorized the applications of system dynamics modeling in supply chain management for inventory management, demand amplification, supply chain reengineering, and supply chain design [96]. Another research review covers the application of system dynamics in simulating international supply chains [85]. SD has been applied for managing the supply chain of rice in a research by Bala et al. [86] to ensure the continuous supply of rice to the consumers efficiently and sustainably subject to supply uncertainty. They presented a system dynamics model to capture non-linear dynamic and complex system with challenges such as seasonal production of rice, the impact of climate change, and lead-time and demand variability. SD was also used in reverse logistics to formulate the complexity of reverse logistic processes due to high level of variability in quantity and quality of used products [31]. SD has also been increasingly used to address the complexity of decision-making in the energy sector [89]. An application of SD in simulating the decision-making in renewable energy supply chains, such as bioenergy (biofuels, solar, etc.) was established by Saavedra et al. [90]. Nasiri et al. proposed a simulation-based optimization of a biomass to electricity supply chain for non-residential buildings under a renewable heat incentive scheme in the UK [34]. They identified the schedule of decision variables over time by optimizing the total (life cycle) cost of (biomass conversion facility's) ownership over subject to a number of technical, operational, and environmental constraints [34]. SD has also been employed in modeling of complex macro-economic problems in the energy sector capturing the long-term scenarios with feedback on capacities and operations [91]. Azade and Arani [91] presented a hybrid system dynamics-mathematical programming model to optimize biodiesel supply chain decisions.

In case of supply chain coordination, an SD approach could be used to investigate the long-term and dynamic complexity coordination mechanisms [31], [28]. SD simulation modeling has also been established for improving information sharing as a means of improving coordination among supply chain members and enhancing a participatory decision-making process [36],[37]. Rendón-Sagardi et al. [38] proposed a SD model to assist decision-makers in improving the coordination across an ethanol supply chain and logistic process. They used SD simulation modeling to observe and analyze the effects of coordination policies.

In the light of the above literature, this paper incorporates formulation of quantity discounts and cost-sharing coordination strategies in case of biomass supply chain for Canada's remote northern communities. A system dynamics modeling is adopted to simulate, analyze and compare these coordination strategies and how they affect the biomass supply chain characteristics. This study attempts to conduct dynamic modeling and simulation of biomass supply chain coordination schemes with a particular application to remote communities.

Considering the literature, supplying biomass for power generation in Canada's remote communities has been highly considered to develop clean energy systems and diminish fossil fuel dependency. Discussed challenges in supplying biomass to remote communities require an efficient biomass supply chain to ensure sufficient biomass supply at a reasonable price to improve the biomass-based electricity generation while minimizing the cost. Through the literature review, we can see that many scholars have established several coordination strategies to improve supply chain efficiency. However, comparing the coordination strategies to select the most efficient one could play a significant role in overcoming the mentioned challenges in supplying biomass for these communities. In this sense, we need to observe the impacts of coordination strategies on the biomass supply chain over time and compare them in various conditions to choose the most efficient one. In this regard, we are dealing with several decisions over time under each coordination scenario with complex trade-offs (and feedback) among them. There is currently no dynamic modeling to compare coordination strategies for the biomass supply chain of remote communities. Therefore, we adopt the SD approach to simulate the dynamic complexity of coordination scenarios in remote communities' biomass supply chain. The impacts of coordination strategies and no coordination strategy on the optimal supply chain arrangements are then analyzed and compared to decide about coordination strategies or no coordination scenario. The remainder of the paper is organized as follows. Section 3 describes the problem and introduces the main assumptions and characteristics of the model. The system dynamics models, as well as the objective functions and constraints of the optimization problem, are explored in section 4. Section 5 presents the case study and relevant simulation and optimization results. Section 6 concludes the study with proposing avenues for future research.

### 3.2. Problem Description

This study attempts to propose a simulation-based optimization model to analyze and compare coordination strategies in biomass supply chains. A biomass supply chain typically consists of suppliers, hubs (as purchase-distribution channels), and remote communities as the end-users of electricity [13]. The hubs purchase biomass according to the suppliers' offered prices and distribute it to the communities by offering them a final price. Figure 14 illustrates the structure of such a biomass supply chain. The paper investigates quantity discounts and cost-sharing strategies to promote coordination in biomass supply chains, where a focus on biomass supply for electricity generation in off-grid remote areas is advocated as to investigate the impact of the above coordination schemes.

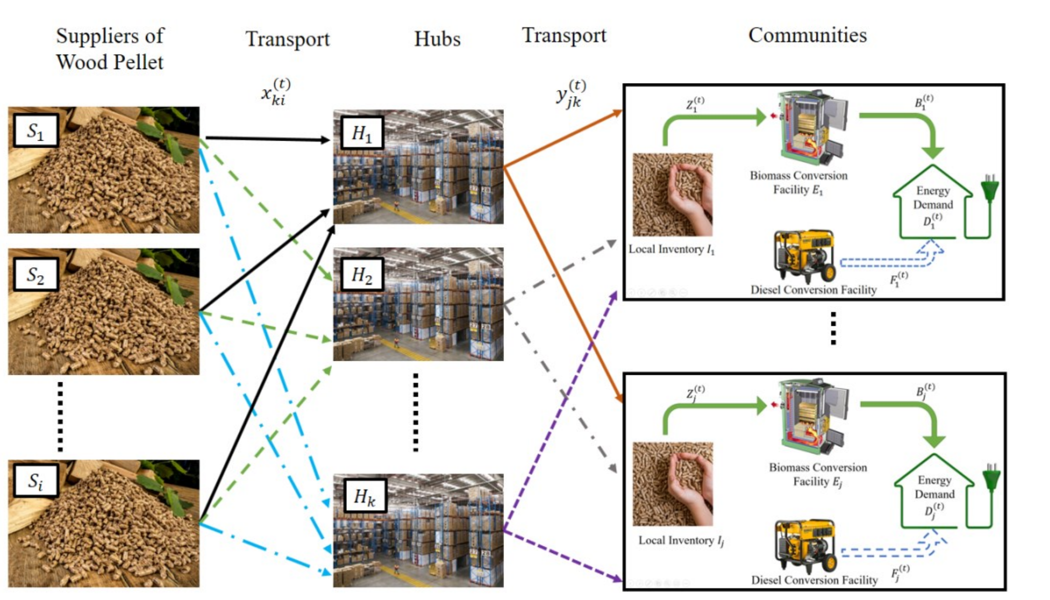



Figure 14- The structure of biomass supply chain for electricity generation.

Wood-based bioenergy systems have been recently supported and developed for Canada's remote communities, while the wood-based bioenergy supply chain is still complex and young in Canada [15], [95]. Wood pellet is one of the wood-based types of residue obtained from the pelletization process. The uniform shape and size of wood pellet and other properties such as low moisture content and high-energy content make the logistics processes easier than other biomass types. [97]–[99]. Accordingly, wood pellet is selected as biomass type for the case of this study.

Establishing a large delivery quantity of biomass from suppliers to communities could promote the economies of scale in biomass supply chains [13]. A quantity discount strategy could encourage large quantities of biomass being delivered to hubs and subsequently to communities. In this sense, the suppliers and hubs are in a position to decide about optimal biomass prices across the supply chain. Besides, the optimal quantities and schedule of the orders at the hub and communities have to be aligned, accordingly to these prices. Alternatively, the coordination could be promoted through a cost-sharing among players to increase the delivery quantities and improve the economies of scale. In this scenario, the selling entity earns an income out of large quantities of sales and compensates a portion of the purchasing and storage entity's cost to stimulate large order quantities. Although the selling agent increases its cost in this situation, it could increase its revenue simultaneously. Based on this scenario, communities, and hubs, as well as hubs and suppliers, share costs to promote collective (larger) quantities through compensation of costs. In doing so, the ratio of cost to be shared with other parties across the supply chain will be a decision variable. Both coordination scenarios are depicted in Figure 15.

In the light of the above coordination mechanisms, we propose a biomass supply chain simulation-optimization model (over a time horizon of *t*) to determine the optimal schedule of the above mentioned decision variables as well as other variables such as inventory levels at hubs and communities while minimizing the total cost of the supply chain. Various technical constraints, including biomass supply capacities, storage capacities, energy demand, and electricity generation capacities, are also incorporated into the model. Using the proposed model, various scenarios on quantity discounts and cost-sharing coordination strategies will be simulated, and their impacts on the optimal supply chain arrangements are then analyzed and compared. As a reference for the methodology presented in section 3, list of variables and parameters of the model presented in the appendix

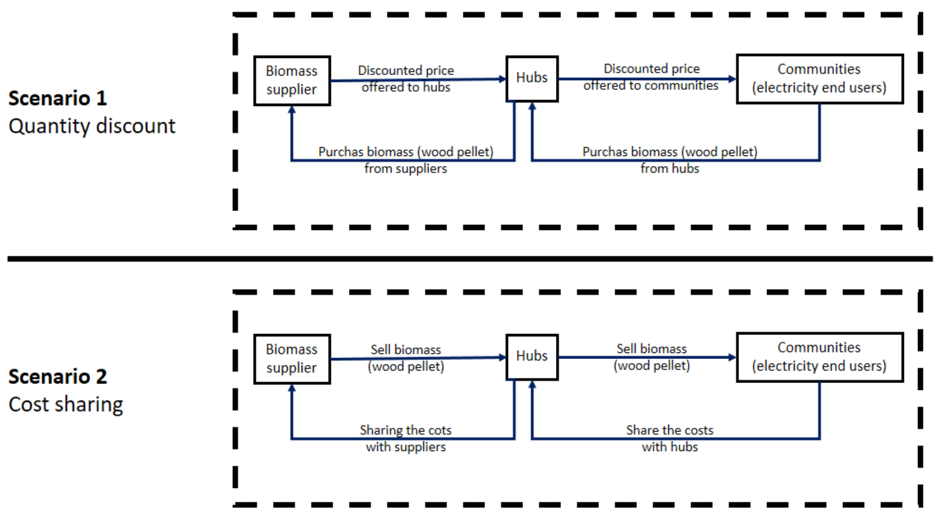



Figure 15- Biomass coordination scenarios.

## 3.3. Methodology

As discussed in section 2, the presented biomasses supply chain deals with a host of several decisions over time under each coordination scenario with complex trade-offs (and feedback) among them. This chain of decisions is also subject to delays resulted from transportation activities that are considerable in case of remote end-user communities. In this sense, we adopt the use of a system dynamics (SD) approach to simulate coordination scenarios over time as well as to incorporate the above mentioned feedback and delays. An SD model will enable us to identify the optimal schedule of decision variables while minimizing the supply chain's total collective cost under each simulated coordination scenario.

In the sequel, the elements and rationale of a system dynamics approach is discussed [81]. Then, the model is presented with details of the specific supply chain problem as well as the variables. The interactions among the players are presented are explored through a causal loop diagram providing a deep understanding of the dynamism resulted from these interactions under each coordination scenario. Then, the model formulations and details of its building blocks including stocks and flows are presented paving the path to turn into structuring the optimization problem.

### 3.3.1. Causal Relationships

A causal loop diagram (CLD) is a representative tool for illustrating the feedback structures of a system. It is built upon presenting the relationships among the variables by causal links with arrows. If the relationship is balancing, with the related variables change in an opposite direction the arrow will be represented by a negative (-) sign while it they change in the same direction, the relationship is considered a reinforcing one represented by a positive (+) sign [82]. The causal relationship diagrams of coordination strategies in a biomass supply chain are presented as follows.

For quantity discount strategy, the causal loop diagram is shown in Figure 16. By offering a discount to hubs, suppliers encourage them to order large quantities and accordingly benefit from the discounted price. With respect to the ratio of order quantity to their capacity, the suppliers offer a discounted price to hubs. On the other hand, the orders are constrained by the supply capacity and hub's storage capacity. In this sense, the suppliers' biomass price offered to hubs is a decision variable for suppliers, while the hubs decide on the order quantity to acquire from suppliers. The hubs in turn offer a discounted price to encourage delivery of larger quantities to communities, which is subject to their storage capacity. In response, communities decide on how much biomass to order from subject to their own storage capacity as well as the available biomass inventory levels at hubs.

For cost-sharing strategy, the causal loop is represented by Figure 17. The communities are willing to order large quantities if they can share a portion of their costs with hubs. Hubs have the motivation for such a cost sharing if it encourages the purchase by communities resulting in higher revenues for hubs accordingly. Such a decision will be subject hubs' storage capacity as well as communities' needs and storage capacities. A similar motivation exists for cost sharing between suppliers and hubs.

Figure 16 and Figure 17 consist of the feedback loops with a loop identifier. There are two reinforcing loops (R1 and R2) in CLDs capturing the coordination strategies. The interaction between order quantity and price reflects the quantity discount strategy (Figure 16). The reinforcing relationship between the cost-sharing ratio and order quantity in Figure 17 represents the cost-sharing strategy. The storage capacities and stocks availability at suppliers, hubs and communities constrains the order quantities and impose balancing loops of B1 to B3. Besides, B4 illustrates a balancing loop imposed by communities' energy demand and electricity generation capacities.

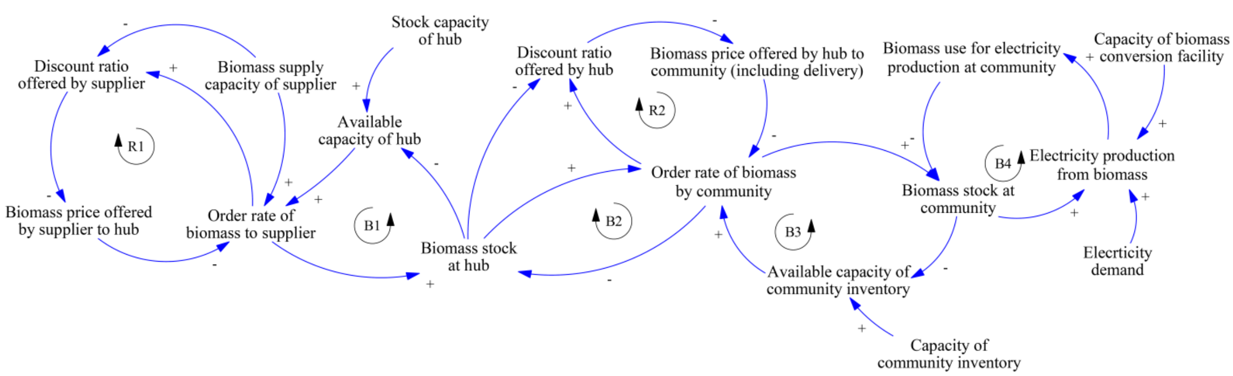



Figure 16- Causal loop diagram of quantity discounts strategy in biomass supply chain.

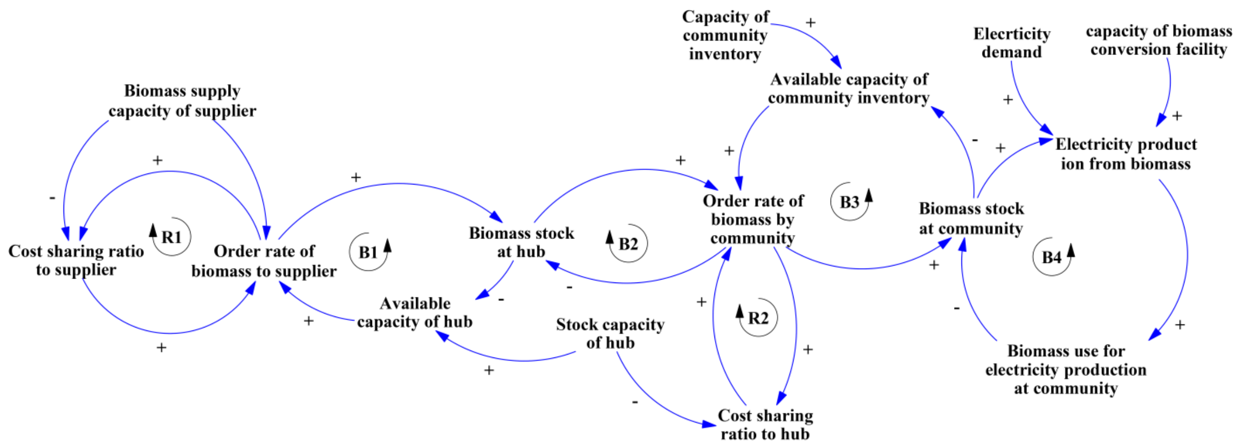



Figure 17- Causal loop diagram of cost sharing strategy in biomass supply chain.

### 3.3.2. Model

A simulation based-optimization model is constructed by developing a stock-flow diagram for each coordination scenarios with respect to the above discussed causal loop diagrams. The proposed SD models are implemented in the VENSIM Professional version 8.1.2 software (Ventana Systems, Inc., Harvard, MA, USA) [100]. The SD models are presented through stock-flow diagrams. . A stock variable (represented by a box) could describe the state of the system at any time step. The double line arrows towards and outwards of the stocks describes the flow variables as inflows to and outflows from the stocks. In this sense, the net flow into a stock shows the rate of change in that stock. Constants (parameters) are the values not changing over time, and auxiliary variables are functions of stocks or constants in forms of objective functions, constraints, and formulated strategies [82]. The models corresponding to quantity discount and cost-sharing strategies are presented in Figure 18 and Figure 19, respectively. In these models, biomass stock levels at communities, cumulative energy conversion cost of communities, biomass stock levels at the hubs, cumulative cost of hubs, and the cumulative total cost of biomass supply chain are considered as stock variables with their inflows and outflows as the flow variables. List of variables and parameters of the model with their descriptions, corresponding players, and units are presented in the appendix A.

The models are simulated and optimized with respect to minimizing the total cost of supply chain, presented in blue in Figure 18 and Figure 19. As shown in Figure 18, this cost is comprised of purchase costs, holding costs at hubs and communities, delivery costs, and bioenergy conversion cost. Under both coordination scenarios, the aim is at identifying the schedule of decision variables (presented in red color in Figure 18 and Figure 19) subject to several discussed constraints. The details of the equations formulating the objective function and constraints of the model are provided in the following section.

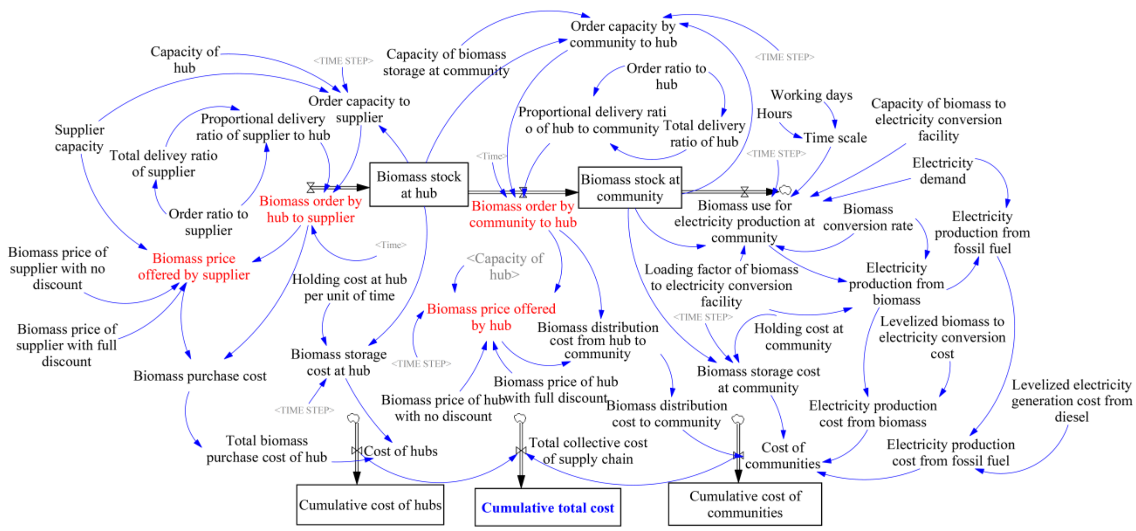



Figure 18- System dynamics model of biomass supply chain coordination under quantity discounts strategy.

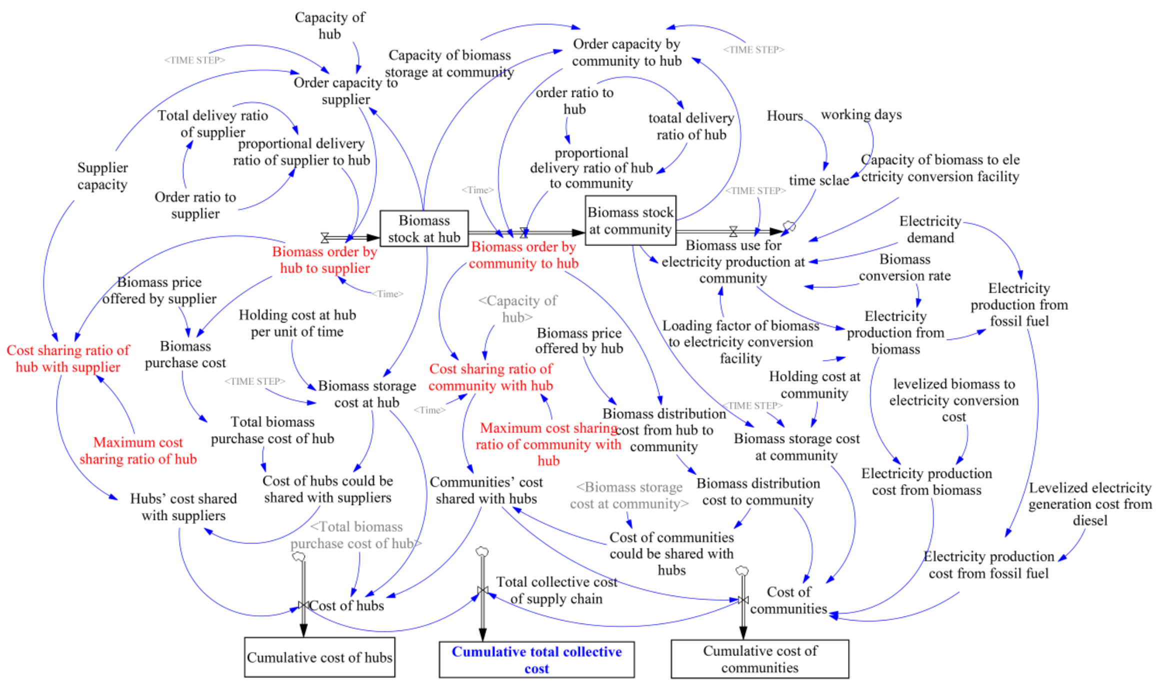



Figure 19- System dynamics model of biomass supply chain coordination under cost sharing strategy.

### 3.3.3. Equations

#### 3.3.3.1. Objective Function for Quantity Discount Scenario

The objective function is the total cumulative cost of biomass supply chain minimized over a time horizon T, as expressed in Equation (1).

Minimize

$$C^{(T)} = \int_{t=0}^{T} c^{(t)} dt \,, \tag{1}$$

where $c^{(t)}$ is the total cost of biomass supply chain at time "$t$ "calculated through Equation (2) under a quantity discount strategy as:

$$c^{(t)} = BPC^{(t)} + BSH^{(t)} + BDC^{(t)} + BSC^{(t)} + BCC^{(t)} + FEC^{(t)} \,, \tag{2}$$

and $BPC^{(t)}$: Biomass purchasing cost at time "$t$" (Equation (3))- (CAD/month), $BSH^{(t)}$: Biomass storage cost at hubs at time "$t$" (Equation (5))- CAD/month), $BDC^{(t)}$: Biomass distribution cost to communities at time "$t$" (Equation (6))- CAD/month), $BSC^{(t)}$: Biomass storage cost at communities at time "$t$" (Equation (8))- (CAD/month), $BCC^{(t)}$: Biomass to electricity conversion cost at time "$t$"(Equation (9))- (CAD/month), $FEC^{(t)}$: Fossil-based energy generation cost at time "$t$" (Equation (11))- (CAD/month). The details of equations are as follows:

$$BPC^{(t)} = \sum_k \sum_i P_{ik}^{(t)}.x_{ki}^{(t)} , \tag{3}$$

where $P_{ik}^{(t)}$: Biomass price offered by supplier "$i$" to hub "$k$" including delivery at time "$t$"- (CAD/$kg$), $x_{ki}^{(t)}$: Biomass order by hub "$k$" to supplier "$i$" at time "$t$"- (kg/month ).

Equation (3) captures the fact that purchasing cost of biomass at time "$t$" is a function of prices offered by suppliers and the corresponding quantities of biomass ordered to hubs.

With quantity discounts, a higher order quantity by a hub will result in a lower price by suppliers. Therefore, suppliers could present a range of biomass prices subject to order quantities. Accordingly, biomass price will be a function of purchase quantity and available supply of biomass. In this sense, Equation (4) represents a biomass pricing strategy based on the quantity discount strategy as:

$$P_{ik}^{(t)} = P_i^u - \left(P_i^u - P_i^l\right)\frac{x_{ki}^{(t)}}{S_i} , \tag{4}$$

where $P_i^u$: Biomass price of supplier "$i$" with no discount- (CAD/$kg$), $P_i^l$: Biomass price of supplier "$i$" with full discount- (CAD/kg) and $S_i$: Biomass supply capacity of supplier "$i$"- (kg).

The biomass storage cost is a function of biomass stock level at the hub and holding cost in hub presented by Equation (5):

$$BSH^{(t)} = \sum_k SH_k^{(T)}.L_k , \tag{5}$$

where $SH_k^{(T)}$: Biomass stock level at hub "$k$" at time "$t$"- (kg), $L_k$: Holding cost at hub "$k$" per unit of time- (CAD/kg).

The biomass distribution cost to communities is presented in Equation (6) as a function of the biomass delivery rate to the communities and biomass price offered by hubs.

$$BDC^{(t)} = \sum_k \sum_j R_{kj}^{(t)}.y_{jk}^{(t)} , \tag{6}$$

where $R_{kj}^{(t)}$ : Biomass price offered by hub "*k*" to community "*j*" including delivery at time "t"- (CAD/kg), $y_{jk}^{(t)}$ : Biomass order by community "*j*" to hub "*k"* at time "*t*"- (kg/month).

The price offered by hubs to communities is calculated through Equation (7) under a quantity discount strategy.

$$R_{kj}^{(t)} = R_k^u - \left(R_k^u - R_k^l\right).\frac{y_{jk}^{(t)}}{H_k} , \tag{7}$$

where $R_k^u$ : Biomass price of hub "*k*" (including delivery) without discount (CAD/kg), $R_k^l$ : Biomass price of hub "*k*" (including delivery) with full discount (CAD/kg), and $H_k$ : Capacity of hub "*k*"- (kg).

As a result of pricing mechanisms presented in Equations (4) and (7), the functions presented by Equations (3) and (6) will be convex in $x_{ki}^{(t)}$ and $y_{jk}^{(t)}$, respectively. Thus, the objective function of the optimization problem (Equation (1)) will be convex in $x_{ki}^{(t)}$ and $y_{jk}^{(t)}$.

The storage cost of inventories at communities is a function of inventory level and unit holding cost as per Equation (8):

$$BSC^{(t)} = \sum_j SI_j^{(t)}.G_j , \tag{8}$$

where $SI_j^{(t)}$ : Biomass stock level at community "*j*" at time "*t*"- (kg), $G_j$ : Holding cost at community "*j*" per unit of time- (CAD/kg).

Finally, Equations (9)-(13) represent the cost of energy conversion, which consists of biomass-to-electricity conversion cost (Equation (9)) and fossil-based energy generation cost (Equation (11)) as follows:

$$BCC^{(t)} = \sum_j B_j^{(t)} . \gamma_j \,, \tag{9}$$

where

$$B_j^{(t)} = z_j^{(t)} . \beta_j . \varepsilon_j \,, \tag{10}$$

and $B_j^{(t)}$ : Electricity production from biomass at time "$t$"- (Kwh/month), $\gamma_j$: Levelized biomass to electricity conversion cost- (CAD/kwh), $z_j^{(t)}$: Biomass use for electricity production at community "$j$" at time "$t$"- (kg/month), $\beta_j$: Biomass conversion rate in community "$j$"- (Kwh/kg), $\varepsilon_j$: Loading factor of biomass electricity generation facility at community "j"- (Dimensionless).

As in case of off-grid communities, the dominant fuel for electricity generation is diesel [101] the cost of generating fossil-based energy (as the alternative to biomass) is the function of the diesel facility's energy output and the levelized cost of energy generation from diesel (Equation (12)). This diesel-based energy output complements biomass in meeting the energy demand of the communities (Equation (13)):

$$FEC^{(t)} = \sum_j f_j^{(t)} \,, \tag{11}$$

where

$$f_j^{(t)} = F_j^{(t)} . \delta_j \,, \tag{12}$$

and

$$F_j^{(t)} = D_j^{(t)} - B_j^{(t)} \,, \tag{13}$$

where $f_j^{(t)}$: Electricity production cost from fossil fuel at time "$t$"- (CAD/month), $F_j^{(t)}$: Electricity production from fossil fuel at time "$t$"- (Kwh/month), $\delta_j$: Levelized electricity generation cost from diesel- (CAD/kwh), $D_j^{(t)}$: Electricity demand in community "$j$" at time "$t$"- (Kwh/month).

On that basis, the cumulative cost of hubs consists of biomass purchasing cost and biomass storage cost (Equations (14) and (15)):

$$V^{(T)} = \int_{t=0}^{T} v^{(t)} , \tag{14}$$

where

$$v^{(t)} = BPC^{(t)} + BSH^{(t)} , \tag{15}$$

and $V^{(T)}$: Cumulative cost of hubs at time "*t*"- (CAD) , $v^{(t)}$: Cost of hubs at time "*t*"- (CAD/month).

The cumulative cost of communities consists of biomass distribution cost to communities and their storage cost as well as cost of energy generation from biomass and fossil fuels calculated through Equations (16) and (17):

$$W^{(T)} = \int_{t=0}^{T} w^{(t)} , \tag{16}$$

where

$$w^{(t)} = BDC^{(t)} + BSC^{(t)} + BCC^{(t)} + FEC^{(t)} , \tag{17}$$

and $W^{(T)}$: Cumulative cost of communities at time "*t*"- (CAD), $w^{(t)}$: Cost of communities at time "*t*"- (CAD/month).

#### 3.3.3.2. Objective Function for Cost Sharing Scenario

Under cost-sharing coordination strategy, the objective function is calculated similar to that of the quantity discount scenario (Equation (1)). However, the amount of cost shared is incorporated into the corresponding players' costs. In this sense, the total cost of biomass ($c^{(t)}$) under cost sharing strategy is calculated as follows:

$$c^{(t)} = v^{(t)} + w^{(t)} + HCS^{(t)} , \tag{18}$$

where $HCS^{(t)}$: Hubs' cost shared with suppliers at time "*t*"- (CAD/month).

The cost amount shared with hubs is deducted from the communities' overall cost and added to hubs' overall cost. Similarly, the amount of shared cost with the suppliers is subtracted from the cost of hubs. Accordingly, the cost of hubs and communities are presented in Equations (19) and (20) respectively:

$$v^{(t)} = BPC^{(t)} + BSH^{(t)} + CSH^{(t)} - HCS^{(t)}, \tag{19}$$

and

$$w^{(t)} = BDC^{(t)} + BSC^{(t)} + BCC^{(t)} + FEC^{(t)} - CSH^{(t)}, \tag{20}$$

where $CSH^{(t)}$: Communities' cost shared with hubs at time "*t*"- (CAD/month).

Under a cost-sharing strategy, large collective order quantities are encouraged by sharing a portion of increasing costs (relative to the extent of the order) between the supply chain players. In this sense, the entity that creates more capacities can gain incentive (as a saving) by sharing the portion of its costs with the rewarding player [71]. In this regard, the suppliers and hubs in this study offer to pay for the portion of the subsequent player's cost to induce them to order larger biomass quantities. There will be an upper limit for cost-sharing which reflects the capacities of rewarding players in offering such an incentive formulated in form of a ratio ranging between zero and one. This ratio reflects the maximum fraction of cost that could be shared at each level of supply chain and is calculated endogenously as a variable of the model while minimizing the total collective cost of supply chain (Equation 1).

According to the above discussion, the portion of communities (end-users) cost that could be shared with each hub (i.e. hubs reward the communities to generate larger amount of bioenergy and thus purchase more biomass) is represented through Equation (21):

$$CSH^{(t)} = \left( BDC^{(t)} + BSC^{(t)} + BCC^{(t)} + FEC^{(t)} \right) . \alpha_{jk}^{(t)}, \tag{21}$$

where

$$\alpha_{jk}^{(t)} = \left( \frac{y_{jk}^{(t)}}{H_k} \right) . \alpha_{jk}^{m(t)}, \tag{22}$$

and

$$0 \le \alpha_{jk}^{m(t)} \le 1, \tag{23}$$

where $\alpha_{jk}^{(t)}$: Cost sharing ratio of Community "$j$" with hub "$k$" at time "$t$"- (Dimensionless), $\alpha_{jk}^{m(t)}$: Maximum cost sharing ratio of community "$j$" with hub "$k$"- (Dimensionless).

In the cost sharing coordination scenario, the hubs offer a fixed price to communities. Accordingly, biomass distribution cost to communities is calculated as follows:

$$BDC^{(t)} = \sum_k \sum_j \left( R_k^u . y_{jk}^{(t)} \right). \tag{24}$$

Now turning to hubs-suppliers cost sharing, Equation (25) calculates the amount of cost that hubs could share with suppliers, as an incentive from suppliers to hubs in order to encourage larger purchases:

$$HCS^{(t)} = \left( BPC^{(t)} + BSH^{(t)} \right) . \alpha_{ki}^{(t)}, \tag{25}$$

where

$$\alpha_{ki}^{(t)} = \left( \frac{x_{ki}^{(t)}}{S_i} \right) . \alpha_{ki}^{m(t)}, \tag{26}$$

and

$$0 \le \alpha_{ki}^{m(t)} \le 1, \tag{27}$$

where $\alpha_{ki}^{(t)}$: Cost sharing ratio of hub "$k$" with supplier "$i$" at time "$t$"- (Dimensionless), $\alpha_{ki}^{m(t)}$: Maximum cost sharing ratio of hub "$k$" with supplier "$i$"- (Dimensionless).

Note that in the cost-sharing scenario, there is a fixed price for biomass. In this regard, the biomass purchase cost is presented by Equation (28):

$$BPC^{(t)} = \sum_k \sum_i \left( P_i^u . x_{ki}^{(t)} \right). \tag{28}$$

#### 3.3.3.3. Model Constraints

In the sequel, the model constraints are presented.

Biomass supply constraint, Equation (29) dictates that the total biomass quantity purchase from each supply source at time "*t*" is bounded by the availability biomass at suppliers:

$$0 \le \sum_{k=1}^{K} x_{ki}^{(t)} \le S_i \,. \tag{29}$$

Similarly, the biomass quantity that each hub could distribute is bounded by its available biomass stock (Equation (30)):

$$\sum_{j=1}^{J} y_{jk}^{(t)} \le SH_k^{(t)} \,. \tag{30}$$

Additionally, as stated by (Equation (31)), for a particular hub (*k*), the biomass quantity transported from all supply sources to the hub at time "*t*" plus the available biomass stock at the hub should not exceed the storage capacity of the hub. Equation (32) also expresses the balance between the storage at each hub and the deliveries from and to it:

$$0 \le \sum_{i=1}^{I} x_{ki}^{(t)} + SH_k^{(t-1)} \le H_k \,, \tag{31}$$

$$SH_k^{(t-1)} + \sum_{i=1}^{I} x_{ki}^{(t)} = SH_k^{(t)} + \sum_{j=1}^{J} y_{jk}^{(t)} \,. \tag{32}$$

Similarly, community's storage constraint (Equation (33)) represents the bound on the biomass quantity that can be delivered to a community in line with its available storage capacity. In this sense, biomass conversion for energy production will also be bounded by the availability of biomass at the community's storage (Equation (34)):

$$0 \le \sum_{j=1}^{J} y_{jk}^{(t)} \le I_j + SI_j^{(t-1)} \,, \tag{33}$$

$$0 \le z_j^{(t)} \le SI_j^{(t)} . \tag{34}$$

Equation (35) captures the relationship between energy conversion and demand at communities as the combined amount of generated bioenergy and fossil-based energy at a community shall meet the energy (electricity) demand:

$$D_j^{(t)} = F_j^{(t)} + B_j^{(t)} . \tag{35}$$

Biomass conversion facility capacity constraint reflects the fact that the actual production output of the facility is bounded by its maximum nominal capacity (Equation (36)):

$$0 \leq B_j^{(t)} \leq ts_j .E_j .\varepsilon_j , \tag{36}$$

where $ts_j$ :ratio of working hours (uptime) of the biomass conversion facility at any time- (h) and $E_j$ : Capacity of biomass-to-electricity conversion facility at community "*j*"- (kw).

In the solution approach, $x_{ki}^{(t)}$and $y_{jk}^{(t)}$ are transformed as ratios to hub-supplier and community-hub channel capacities, respectively. This makes the corresponding decision variables values ranging between 0 and 1:

$$x_{ki}^{(t)} = \delta_{ki}^{(t)} . X_{ki}^{(t)} \tag{37}$$

$$y_{jk}^{(t)} = \Phi_{kj}^{(t)} . Y_{jk}^{(t)} \tag{38}$$

where $X_{ki}^{(t)}$: Order capacity to supplier "$i$" by hub "$k$" at time "$t$"- (kg/month), $Y_{jk}^{(t)}$: Order capacity to hub "$k$" by community "$j$" at time "$t$"- (kg/month), and decision variables of $\delta_{ki}^{(t)}$: Order ratio to supplier "$i$" by hub "$k$" at time "$t$" and $\Phi_{kj}^{(t)}$: Order ratio to hub "$k$" by community "$j$" at time "$t$":

$$0 \leq \delta_{ki}^{(t)} \leq 1 \tag{39}$$

$$0 \leq \Phi_{kj}^{(t)} \leq 1 \tag{40}$$

In addition to the above-described formulas, a full list of these equations as implemented in Vensim model is presented in the Appendix A.

## 3.4. Case Study and Results

In this section, to show the applicability of the proposed models and the impact of coordination strategies, we consider a real case study. This will be followed by analysis of the results with respect to certain characteristics and assumptions in the proposed models. We then turn to interpretation of the impact of alternative coordination strategies of quantity discounts and cost sharing. Also sensitivity analysis is conducted to investigate the parameters variations on the results of each scenario. On that basis, further insights will be provided by comparing the results obtained under these strategies with respect to cost efficiency gains and the level of biomass by the communities.

### 3.4.1. Case Study

The case study contains three remote and off-grid communities in the north of Canada as electricity end-users, which are Kangigsujuaq (KA), Salluit (SA), and Ivujivik (IV) in the north of Quebec. Off-grid diesel facilities currently produce electricity. The biomass type is assumed as wood pellet, which can only be supplied to communities by waterways (Figure 20). The communities have small economies of scale because of their size and remoteness. The case study considers two hubs to supply wood pellet to communities and receiving biomass from six suppliers. The first hub is in Eastmain in the west of Quebec (QC), supplied by three suppliers in the provinces of QC, NB, and the state of Maine. The second hub is in Bathurst in the northeast of New Brunswick and could order biomass to three suppliers in QC (QC1, QC2, and QC3). Considering one month time step in the model, it is assumed that the hubs can receive the orders during the time between April ($t$ = 3) and August ($t$ = 7), and the delivery time to communities is from April ($t$ = 3) until the end of September. The data used in this study are derived from [13] and provided in the Appendix A.


Figure 20- Locations of case study communities and hubs.

### 3.4.2. Results Analysis

Vensim optimization platform employs a Powell hill-climbing algorithm [102] to search for the optimal schedule of the variables. We consider a time horizon of 12 months to reflect on the seasonality effects with respect to biomass supply and local climate. Minimizing the total collective cost of biomass supply chain subject to constraints presented by Equations (29) - (40) will result in search for optimal decisions on the delivery schedule of biomass, offered prices and cost-sharing ratios leading to biomass and diesel conversion facilities' operational plans as well as inventory levels at hubs and communities. The simulation based-optimization cycle will be conducted over the time horizon. Figure 21 to Figure 29 show the results of the sequential optimization and simulation processes for a representative supplier, hub, and community.

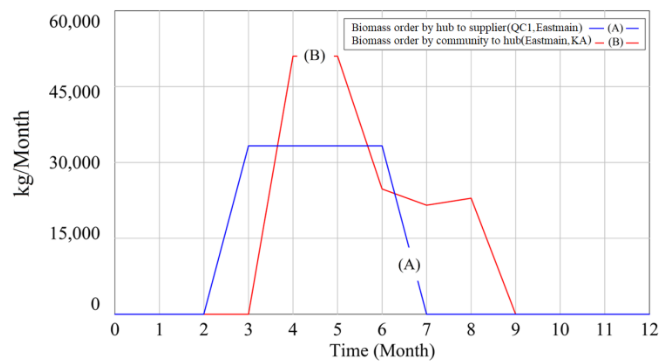



Figure 21- Optimal biomass orders to supplier and hub.

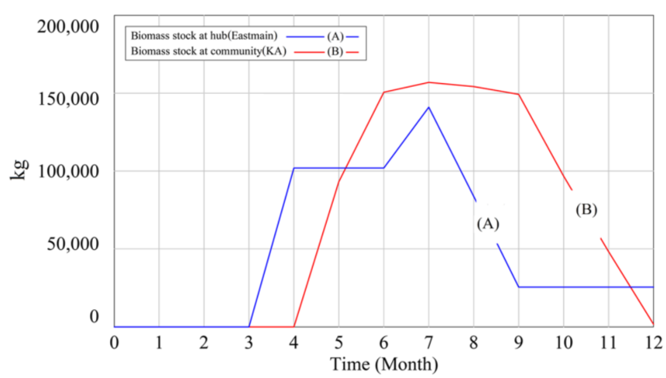



Figure 22- Hub and community inventory levels.

As shown in Figure 21 and Figure 22, biomass stock level starts to increase one month after ordering to suppliers and remain stable at 102,000 for two months, as there is no change in the purchasing and distributing of biomass during this time. The hub inventory level reaches to a pick of 141,000 due to a reduction in biomass delivery to communities for certain periods of time. This reduction is the result of limitations caused by storage and energy conversion capacities. As depicted by Figure 21 and Figure 22, the delivery rate to the community is affected by stock levels at hubs as well as community inventory. The community starts ordering from the hub once at $t = 3$ when there is biomass availability at the hub. This order increases to a maximum of 50,000 kg, at which we approach the capacity limitations. Consequently, the community inventory experiences a reduction with reduced deliveries to communities and hubs starting at $t = 7$.

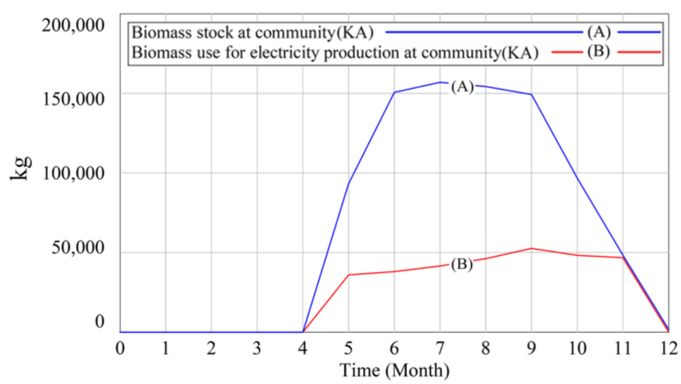



Figure 23- Biomass utilization and stock levels at community (KA).

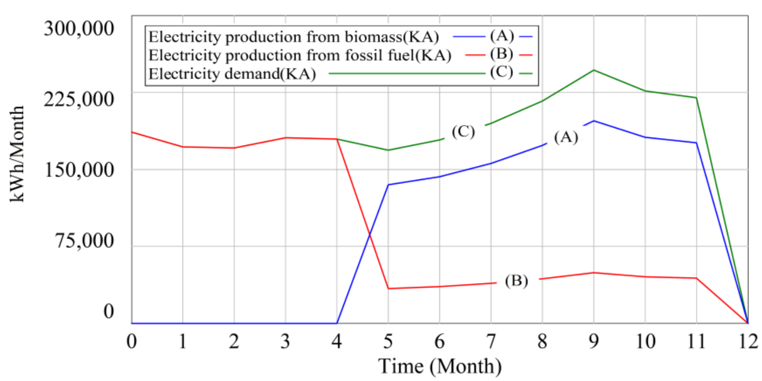



Figure 24- Electricity production schedule from alternative sources.

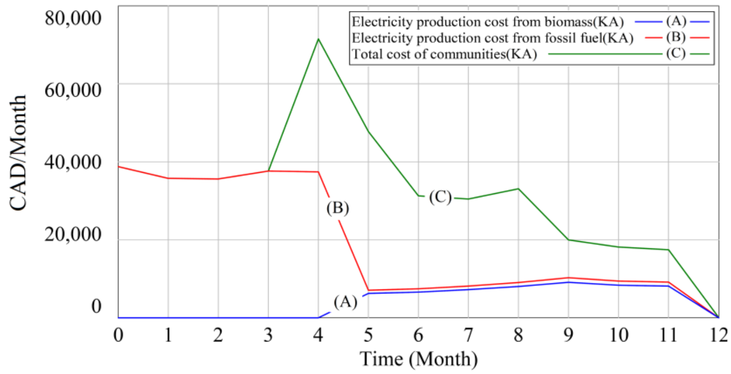



Figure 25- Electricity production costs from alternative sources and in total.

According to results presented in Figure 23 and Figure 24, as soon as the community establishes a biomass storage, the biomass utilization ratio at the community and electricity production by biomass conversion facility are increased peaking at 52,532 kg and 197,520 kwh at the peak demand time ($t$ = 9), respectively. At this time, the community reaches a 4 to 1 ratio for biomass and fossil fuel conversion facilities' utilization.

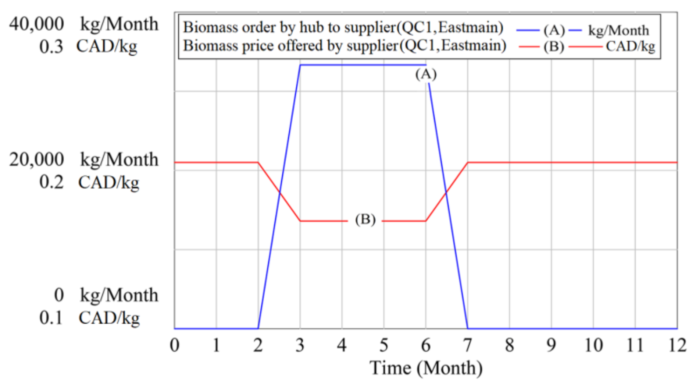



Figure 26- Biomass order to supplier and the corresponding supplier's price.

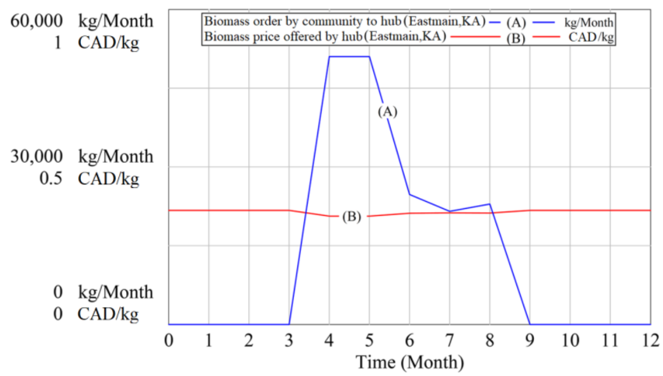



Figure 27- Biomass order to hub and the corresponding hub's price.

According to Figure 26, a hub benefits from a discounted price if it orders more from suppliers. Once a steady flow of order is established, the discounted price reaches an equilibrium level. Figure 27 reveals the optimal price and order quantity for communities. It is recognized that a community is also motivated to order larger quantities of biomass to benefit from a discounted price subject to constraints on storage and energy demand.

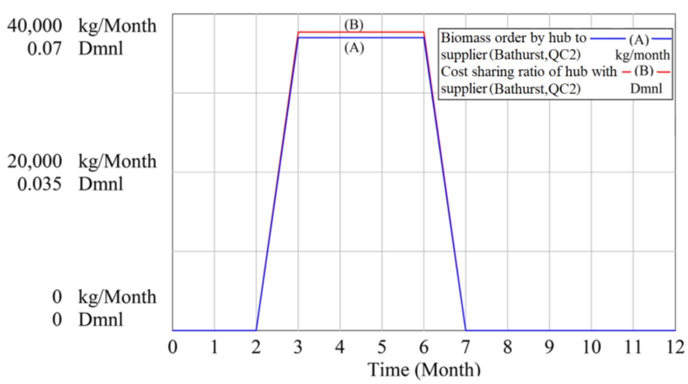



Figure 28- Biomass order to a supplier and the corresponding cost sharing with a supplier.

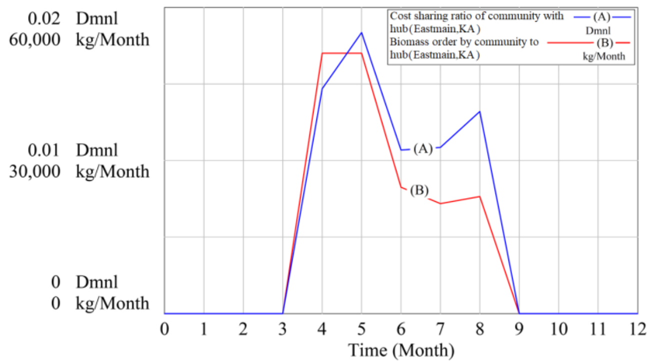



Figure 29- Biomass order to a hub and the corresponding cost sharing with a hub.

As depicted in Figure 28 and Figure 29, a supplier compensates a portion of a hub's cost. Subsequently, a hub compensates a portion of a community's cost. The results show that a cost sharing strategy could encourage the players to order larger quantities subject to constraints on storage capacities. Figure 30 presents that the cumulative cost of hubs increases while the hubs continue to order and hold biomass inventories between $t = 3$ and $t = 7$. The cost of hubs reaches a maximum of 178,204 when there is no coordination.It reaches to a maximum of 151,705 in case of quantity discounts strategy and a maximum of 165,092 in case of cost-sharing straegy, showing savings in both coordination cases in comparison with no coordination. In this regard, the quantity discount strategy  will be the preferred coordination from hubs' perspective.

Figure 31 presents that the cumulative cost of communities is not much impacted with or without coordination strategies. However, quantity discount strategy corresponds to the lowest level of cost for communities. The highest cost of communities for quantity discounts, cost-sharing, and no coordination scenario will be 1,486,210, 1,491,360, and 1,496,660, respectively. As such, the communities might also prefer a quantity discount strategy.

As presented in Figure 32, the cumulative discount offered to hubs and the cumulative cost sharing with suppliers reach a maximum of 26,498.4 and 18,410.2, respectively. In this regard, the suppliers' preference strategy would be cost sharing.

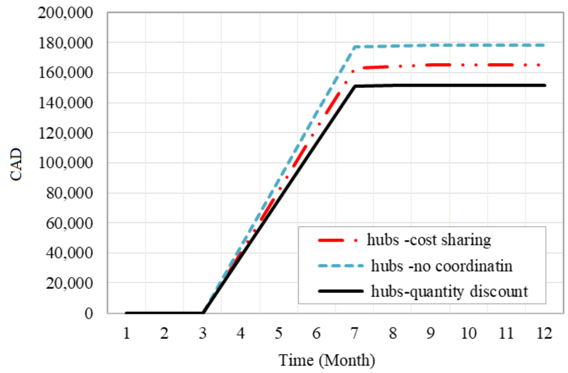



Figure 30- Cumulative cost of hubs.

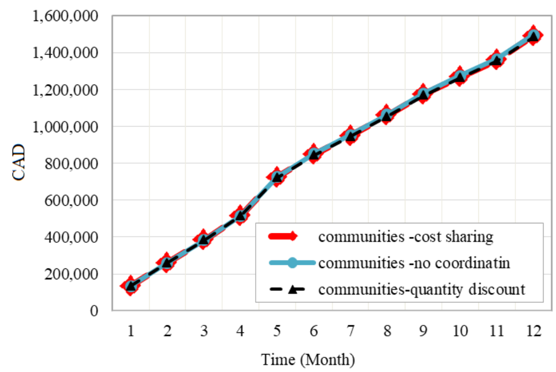



Figure 31- Cumulative cost of communities.

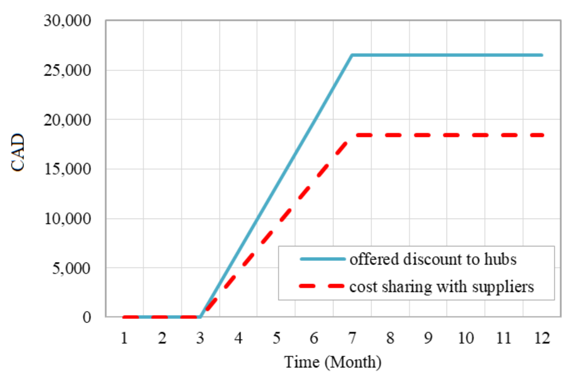



Figure 32- Cumulative cost of suppliers in coordination scenarios.

### 3.4.3. Sensitivity Analysis and Discussion

In this section, the impact of biomass price and storage capacities on the players' costs under coordination scenarios are investigated using the Vensim sensitivity analysis platform [100]. This analysis is performed by varying the two mentioned parameters across a range represented by a uniform distribution while other parameters are kept fixed. The lower and upper limits of variations are based on decreasing and increasing the initial values by 40%.

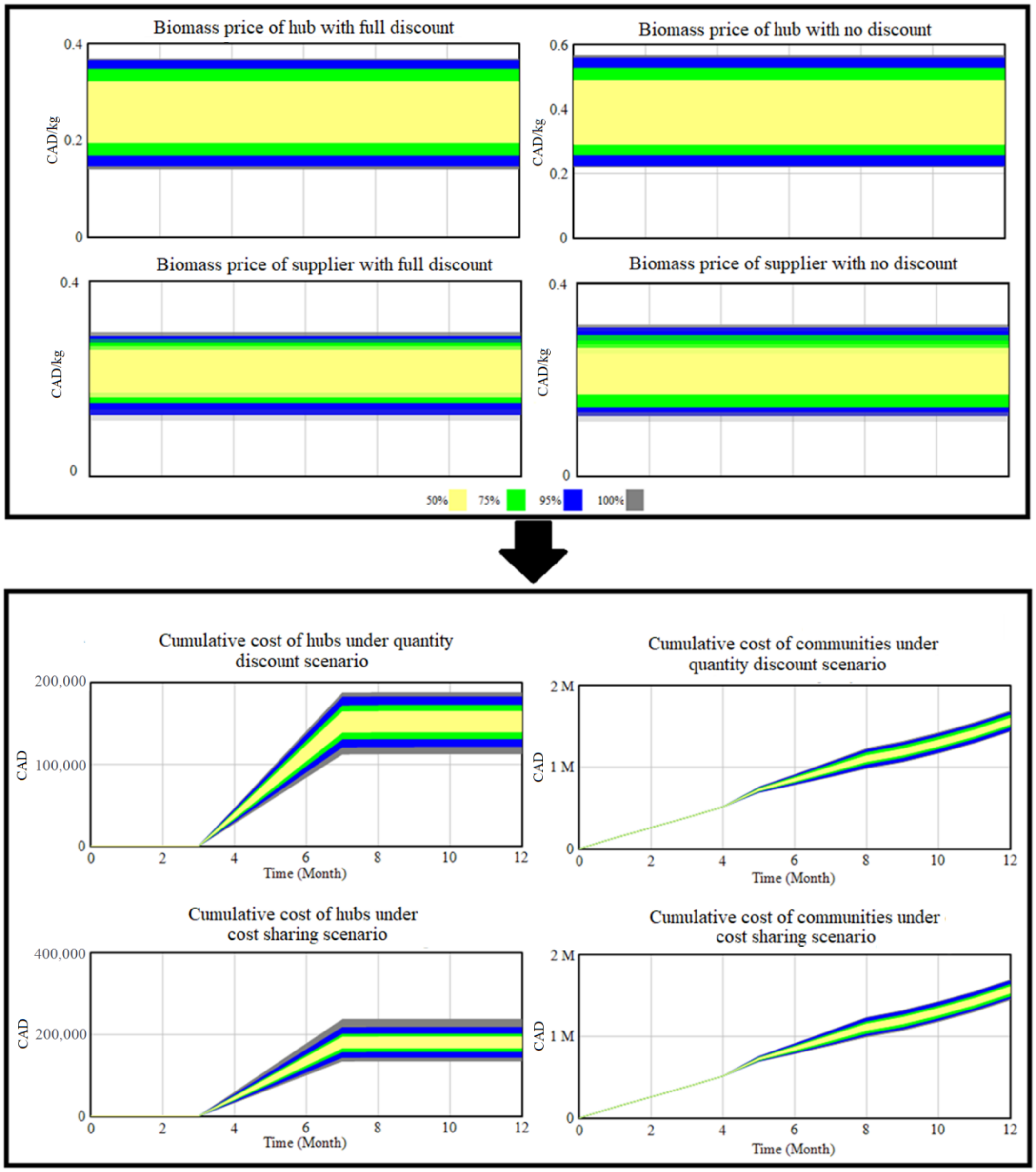



Figure 33- Sensitivity of cumulative cost of hubs and communities under quantity discount and cost sharing scenarios with variation in biomass price.

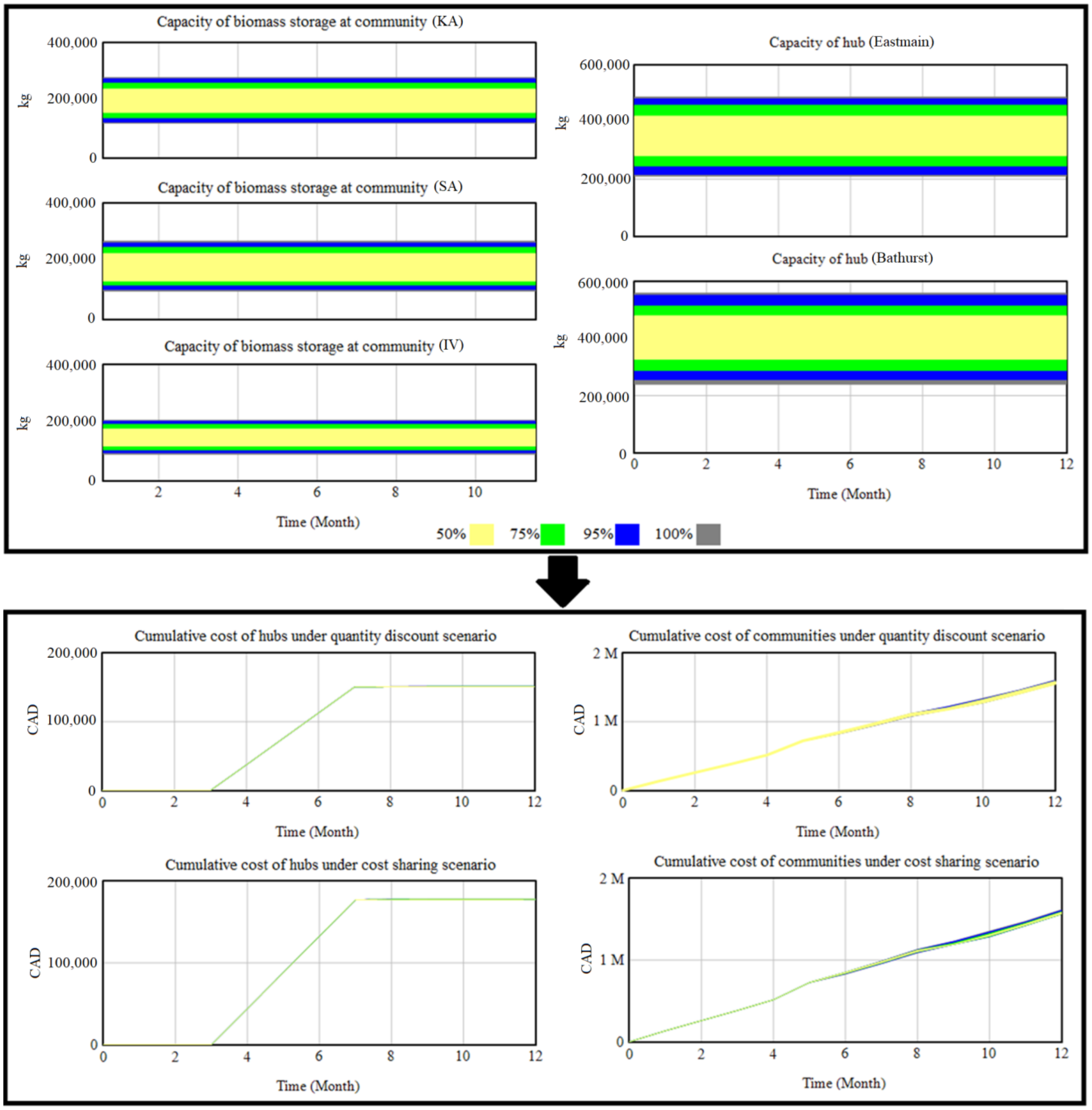
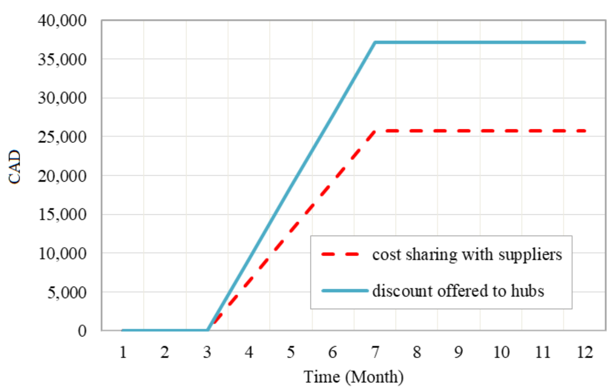



Figure 34- Sensitivity of cumulative cost of hubs and communities under quantity discount and cost sharing scenarios with variation 165.

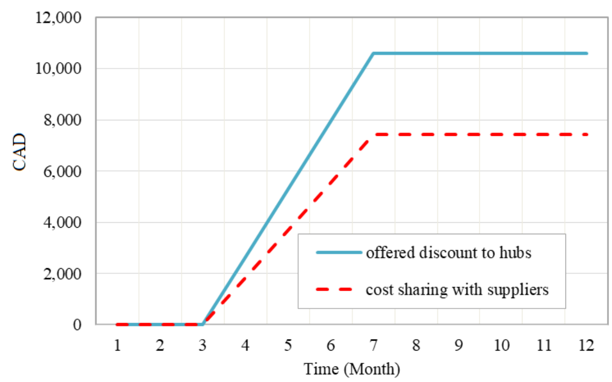
According to Figure 33, utilizing more expensive or cheaper biomass could impact the cost of hubs and communities positively under both coordination scenarios. The hubs' cost variation will impact the amount of cost-sharing offered to suppliers as well. The offered discounts are reinforced by biomass price variations. Accordingly, biomass price could play a significant role in performance of coordination scenarios to an extent that change the players' preferred choice of coordination strategies. Figure 34 shows that the storage capacities do not have a significant impact on costs of hubs and communities due to biomass supply limitations. In this sense, the players' costs are more sensitive to biomass price variations than variations in storage capacities.

With varied biomass prices and storage capacities, the players will have different preferences of coordination strategies. The size of communities and the number of players at each level could impact the extent of the competition and change the results. In this sense, the coordination strategies are compared under the following scenarios:

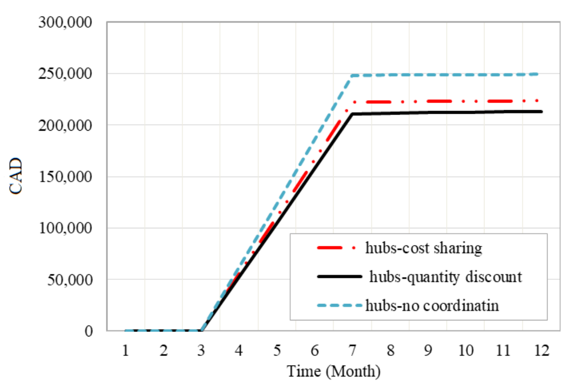
- <u>Opting for more expensive or cheaper biomass types</u>: to investigate the impact of such scenarios, upper and lower bounds of biomass price (price with full discount and price without discount) are increased by 40% and decreased them by 60% while other parameters are kept fixed.



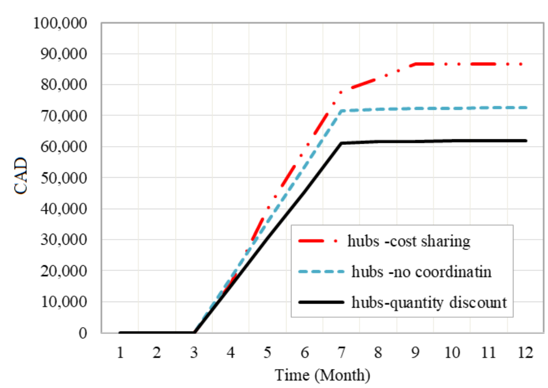

**(a)**



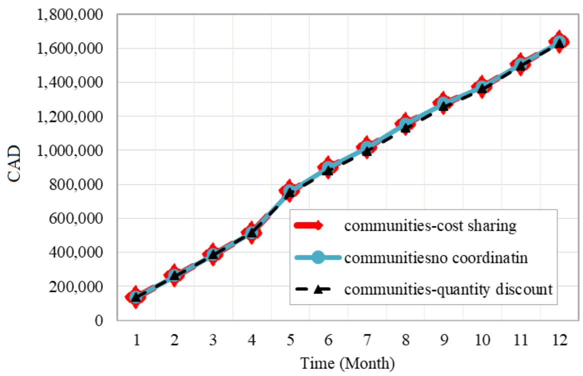

**(b)**



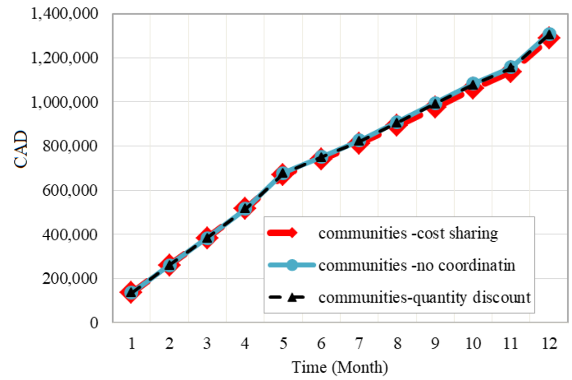

**(c)**




**(d)**




(e)




(f)

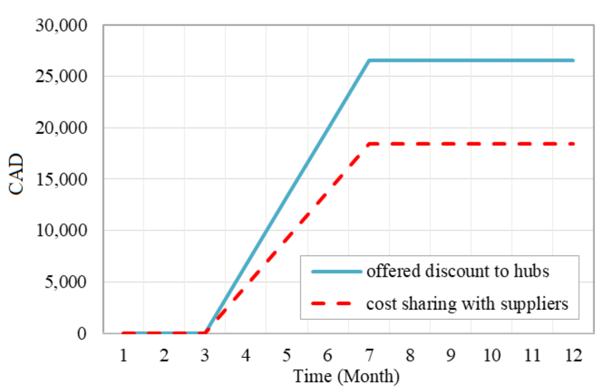
Figure 35- Cumulative costs with variations in price for (a) suppliers in case of more expensive biomass type, (b) suppliers in case of cheaper biomass type, (c) hubs in case of more expensive biomass type, (d) hubs in case of cheaper biomass type, (e) communities in case of more expensive biomass type, (f) communities in case of cheaper biomass.

Figure 35a,b present the cumulative cost of suppliers under coordination scenarios when choosing more expensive or cheaper biomass types, respectively. As shown in Figure 35a,b, using more expensive or cheaper biomass types will not impact suppliers' preferred coordination scenarios. According to Figure 35b, decreasing the biomass price by 60% leads to a discount amount of CAD 10,599.4 and cost sharing of CAD 7,423.55 equivalent to 60% and 59% reductions in discount and cost sharing, respectively. In this regard, the discount amount is reduced slightly more than cost sharing in case of cheaper biomass types. Similarly, increasing biomass price by 40% increases suppliers' cost, in case of quantity discount and cost-sharing scenarios by CAD 37,097.8 and CAD 25,740.1, respectively (Figure 35a). In this scenario, the suppliers' cost is slightly more sensitive to price in quantity discount strategy in comparison with a cost-sharing strategy. The reason is that the suppliers should compensate the storage cost of hubs in a cost-sharing scenario no matter what biomass price is. In contrast, under a quantity discount strategy, discount rates will vary by biomass price variations. In this sense, suppliers prefer a cost-sharing strategy.

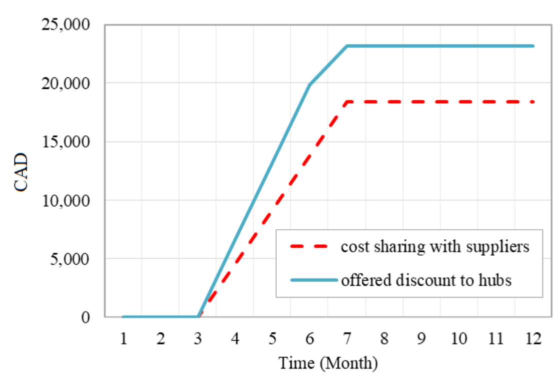
In the case of cheaper biomass type, hubs' cost for the cost-sharing scenario is de-creased by 50% and for quantity discount and no coordination scenarios it is decreased by 60%. As depicted in Figure 35d, hubs' cumulative cost reaches to CAD 86,754.1 under the cost-sharing scenario, and to CAD 72,537.4 and CAD 61,938, in no coordination and quantity discount scenarios, respectively. Accordingly, hubs will prefer a quantity discount strategy when using a cheaper biomass type. As biomass price increases, both coordination scenarios have more savings compared with the no coordination scenario (Figure 35c). In case of more expensive biomass, the cost of hubs increases to a higher level under quantity discounts, CAD 223,467, in comparison with cost-sharing, that reaches to CAD 213,064. In this sense, cost sharing will be the preferred coordination scenario from hubs' perspective in case of more expensive biomass.

For communities, a cost-sharing scenario creates more savings in comparison in the case of a cheaper biomass type. As depicted in Figure 35f, cumulative cost of communities under cost-sharing, quantity discount, and no coordination scenarios will reach a maximum of CAD 1,287,080, CAD 1,304,210, and CAD 1,308,720, respectively, with biomass price decreasing by 60%. In this regard, communities' preferred scenario will be the cost-sharing in case of cheaper biomass types. As biomass price increases, communities' cost in a cost-sharing scenario will increase with a higher rate in comparison with other scenarios. With price increases at a rate of 40%, communities' cost for cost sharing, quantity discounts, and no coordination scenarios will reach to CAD 1,637,310, CAD 1,628,360, and CAD 1,637,310, respectively (Figure 35e). As such, in case of more expensive biomass types, communities will prefer the quantity discount strategy.

- Having larger or smaller storage capacities at hubs and communities: Storage capacities are increased and decreased by the same rate of 40% while fixing all other parameters to investigate the sensitivity to the capacity assumptions.




(a)




(b)

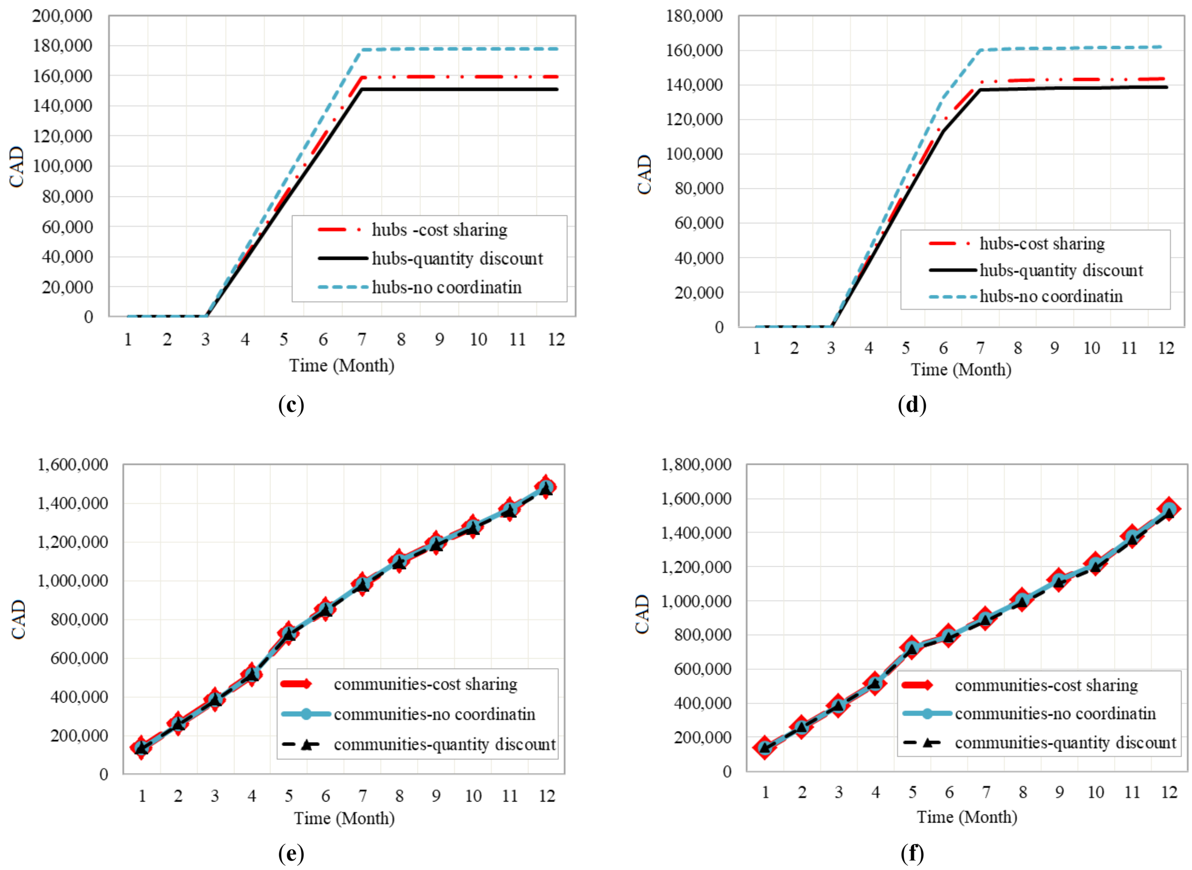



Figure 36- Cumulative costs with variations in storage capacities for (a) suppliers in case of larger storage capacities, (b) suppliers in case of smaller storage capacities, (c) hubs in case of larger storage capacities, (d) hubs in case of smaller storage capacities, (e) communities in case of larger storage capacities, and (f) communities in case of smaller storage capacities.

Figure 36a,b depict the variations in discount and cost-sharing amounts subject to increases and decreases of storage capacity (by a rate of 40%), respectively. As shown, storage capacity variations will not significantly impact the costs. This is due to the fact that biomass supply capacities limit the delivery amounts, and thus, having higher storage capacities could not necessarily lead to increase in delivery amounts. According to Figure 36a, suppliers will still prefer the cost-sharing strategy if storage capacities increase. Similarly, storage capacity reduction does not contribute to considerable decrease in cost-sharing amount (only a reduction rate of 1%). In contrary, reduction of storage capacities results in discount amount being reduced by 12% reaching a maximum of CAD 23,147.1. This is still higher than cost of suppliers under the cost-sharing scenario (CAD 18,426.3). It is thus expected that a quantity discount strategy is preferred by suppliers in cases of very small storage capacities (such that to limit the deliveries).

As depicted in Figure 36c,d, both coordination scenarios will contribute to hubs' cost savings compared with a no coordination scenario in case of varied storage capacities. If storage capacities are decreased by 40%, hubs cost will be reduced by 13% and 8% reaching to CAD 143,514 and CAD 138,738 in cost-sharing and quantity discount scenarios, respectively (Figure 36d). The results show that hubs' cost in cost-sharing scenario is very close to that of quantity discount scenario. This reflects the fact that smaller storage capacities lead to smaller order quantities resulting in lower discounts. As such, cost-sharing will be the preferred strategy in case of very small storage capacities. On the other hand, communities and hubs will be motivated to order larger quantities if they have larger storage capacities. In this sense, a quantity discount strategy will be preferred by them in case of larger storage capacities. As shown in Figure 36c, hubs' cumulative cost under quantity discount, cost-sharing, and no coordination scenarios are CAD 151,215, CAD 159,303, and CAD 177,714, respectively, in case storage capacities increase by 40%.

Figure 36e,f show that storage capacity variations will not impact communities' cost significantly. However, with larger storage capacities, a communities' cumulative cost will decrease further under quantity discount and cost-sharing as well as no coordination scenarios reaching to CAD 1,474,320, CAD 1,483,390, and CAD 1,483,400 (Figure 36e). This reflects the fact that communities could order larger quantities when they have larger storage capacities to benefit from higher discounts and cost-sharing. Additionally, the share of electricity production from biomass will increase in both coordination scenarios with larger storage capacities. The results show that increasing storage capacities by 40% leads to improving the share of electricity production from biomass by 17% in both coordination scenarios. The share of biomass in electricity generation ranges from 34% to 40% in coordination scenarios when capacity storage increases by 40%. In this case, communities will prefer quantity discounts due to higher savings. Smaller choices for storage capacities do not have an impact on communities' preference of coordination scenarios but increase communities' cost under all scenarios, with quantity discounts scenario presenting the lowest cost at CAD 1,515,060 (Figure 36f).

- Dealing with larger or smaller communities: Obviously, large communities are expected to demand more electricity compared with smaller communities. Accordingly, electricity demand is increased up to 70% to investigate the effect of larger communities. In addition, electricity demand is decreased by 40% to capture the effect of dealing with smaller communities. Note that all other parameters are kept fixed.

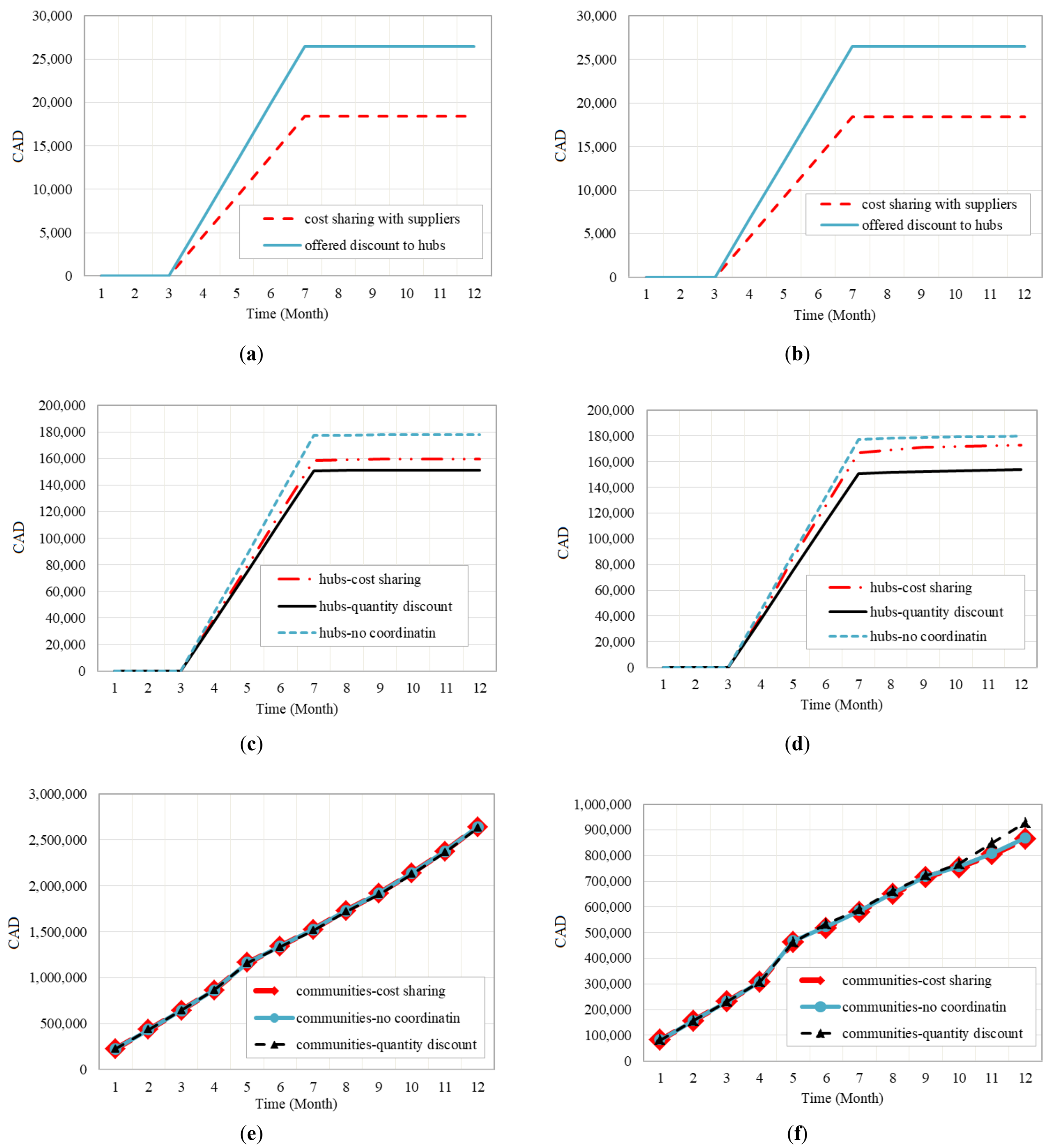



Figure 37- Cumulative costs with variations in communities' size for (a) suppliers in case of larger communities, (b) suppliers in case of smaller communities, (c) hubs in case of larger communities, d) hubs in case of smaller communities, (e) communities in case of larger communities, and (f) communities in case of smaller communities.

Figure 37a,b present suppliers' cost for larger and smaller communities, respectively. The results show that communities' size does not impact the amount of discount offered to hubs. Accordingly, suppliers' cost will not be affected by communities' size in a quantity discount scenario. Additionally, communities' size does not contribute to considerable variations in cost-sharing. According to Figure 37b, cost sharing increases almost by 1% and reaches to a maximum of CAD 18,426.4 in case of dealing with smaller communities. This slight growth is due to reduction in biomass use, increasing the hubs' storage cost, and thus, slightly increasing the cost sharing with suppliers. Overall, suppliers will prefer a cost-sharing scenario for any size of communities.

As depicted in Figure 37d, in case of dealing with smaller communities, hubs' cost increases to CAD 172,959, CAD 153,807, and CAD 180,156 under cost-sharing, quantity discounts, and no coordination scenarios, respectively. In this case, the cost-sharing strategy results in the highest increase in hubs' cost (by 4%). In this sense, the quantity discount strategy will be preferred by hubs in case of dealing with small communities as lower demand and lower delivery of biomass lead to increasing the storage cost of hubs. In addition, communities will share a larger portion of their cost with hubs in case of smaller communities. As depicted in Figure 37c, in case of dealing with larger communities, cost of hubs decreases at a higher rate in cost-sharing scenario compared with other scenarios. Hubs' cost reaches to a maximum of CAD 159,494 with cost-sharing and CAD 151,404 with quantity discount scenario. In this regard, in case of dealing with large communities, cost sharing might be preferred by hubs.

Turning to communities' cost, smaller communities will prefer a cost-sharing strategy, according to Figure 37f. The cost sharing will increase in case of smaller communities to motivate larger order deliveries. A larger biomass delivery quantity is expected for cost sharing compared with a quantity discount and no coordination scenarios. Accordingly, the highest share of biomass in electricity generation, 46%, corresponds to the cost-sharing scenario. As shown in Figure 37e, communities' cost increased and reaches a maximum of CAD 2,642,870, CAD 2,631,370, and CAD 2,642,870 for cost-sharing, quantity discount, and no coordination scenarios, respectively. The share of biomass in generating electricity for larger communities is almost 24% under all scenarios. Considering the costs, a quantity discount might be a preferred scenario for large communities.

- Increasing the Number of Parties at Each Level of Supply Chain: In case of having more suppliers, total biomass supply amount could increase. Similarly, having more hubs and communities leads to increasing the total storage capacities as well as higher electricity demand.

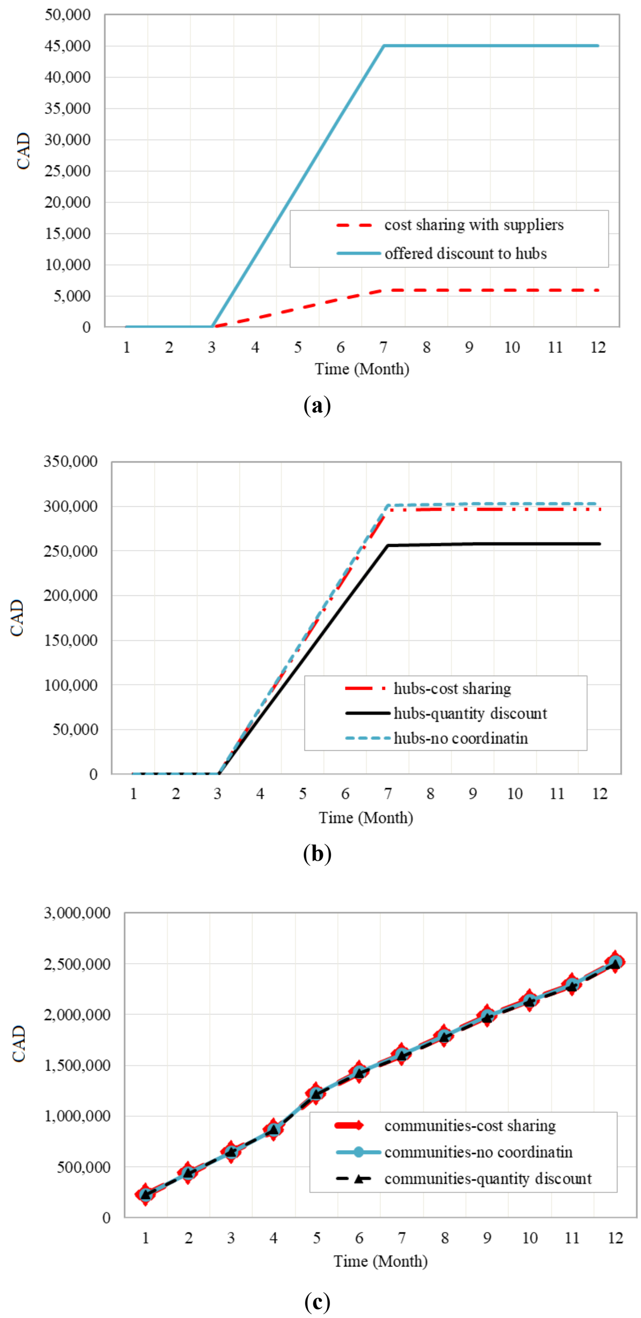



Figure 38- Cumulative costs with more players at each level for (a) suppliers, (b) hubs, and (c) communities.

In the case of having more players, it is expected to have more biomass supply, more storage capacities, greater demand for electricity, and a higher capacity for electricity generation. As depicted in Figure 38a, this results in a cost-sharing decrease by 67% (reaching to CAD 5977), while increasing the offered discount to hubs by 70% (reaching to CAD 45,047). In this scenario, a cost-sharing strategy will be the preferred coordination strategy from suppliers' perspective.

According to Figure 38b, cost of hubs increases and reaches to CAD 296,987, CAD 257,919, and CAD 302,964 in case of cost-sharing, quantity discounts, and no coordination in a supply chain with more players involved. In this situation, cost sharing results in the highest cost increase for hubs by 80%. As such, hubs will prefer quantity discounts in case of a biomass supply chain with more players at each level.

Turning to communities, Figure 38c shows that having more players at each level will not impact communities' preference for coordination scenarios. In this sense, communities' preference is still a quantity discount strategy.

In summary, suppliers would prefer a cost-sharing strategy. Variations in price, communities' size and number of players at each level of supply chain would not impact their preference. However, size of storage capacities impact suppliers' cost and could result in quantity discount strategy becoming their preferred coordination strategy. On the other hand, hubs would prefer a quantity discount strategy, and having more players at each level would not impact their preference. The hubs benefit more from this strategy than cost-sharing and no-coordination strategies in case of cheaper biomass types, larger biomass capacities, and dealing with small communities. However, in case of expensive biomass types, hubs' preference strategy could be the cost sharing. Communities' preferred strategy is quantity discounts, and having more players would not impact their preference. They also benefit more from this strategy in case of expensive biomass types. Similarly, larger communities are expected to have higher savings and a higher share of biomass in electricity generation under quantity discounts compared with other scenarios. Additionally, communities' cost efficiency and biomass share in electricity generation would be improved by a quantity discount strategy under any storage capacity scenario. However, a cost-sharing strategy would be the preferred strategy of small communities in case of cheaper biomass types.

## 3.5. Summary

This study proposed a simulation-optimization model to analyze alternative biomass supply chain coordination strategies with a case study in Canada's off-grid northern communities. The electricity generation from biomass was considered as an alternative for diesel. The quantity discounts and cost-sharing coordination scenarios were compared based on their impact on minimizing total cost of biomass supply chain. We created a model that incorporated the coordination strategies to biomass supply chain by considering the costs associated with the supply, storage, and use of biomass, as well as the costs of electricity generation from biomass and diesel throughout a time horizon of 12 months. In this regard, we were able to investigate the impact of coordination scenarios on the overall cost of players as well as the cost performance of the biomass supply chain. With a cost minimization objective, the optimal biomass ordering schedule, electricity production schedule (from biomass and diesel), biomass inventories at hubs and communities, as well as price discounts (under quantity discount strategy) and ratios of cost sharing (under cost-sharing scenario) were identified. The results indicated that the quantity discounts and cost-sharing strategies effectively improved the cost efficiency of hubs and communities by improving the economies of scale. In comparison, the case study results shows that hubs and communities preferred the adoption of quantity discounts coordination strategy due to incurring lower overall costs in this scenario compared to cost-sharing strategy. In contrast, suppliers benefit more from the cost-sharing scenario. The comparison of results under different circumstances pointed to the significant role of coordination strategies in improving the cost efficiency as well as the level of biomass-based electricity generation while the players have different preferences in choice of coordination strategies.

Since economic gains are not necessarily the only aim of bioenergy production, social and environmental issues could also be considered to provide a more comparative analysis of the coordination strategies for biomass supply chain of remote communities [43]. In this sense, the simulation-optimization model applied in this study to investigate the coordination strategies could be extended to a multi-objective model to capture the biomass supply chain's environmental and social gains. The disposal or utilization of ash residues from biomass combustion is also a defining factor for adoption of biomass in communities as an alternative source for electricity generation. The ash can be used in cement and building materials production as an additive, added as an asphalt filler, or added to compost as a fertilizer [44]. It is also imperative to consider demand and supply uncertainties and analyze other forms of coordination strategies such as risk-sharing contracts.

# Chapter 4: Conclusions and Recommendations

## 4.1. Summary and Conclusions

Biomass is an attractive renewable source of energy in remote communities to reduce the reliance on fossil fuels. Remoteness and dispersion of communities with a small scale of demands are among the key barriers to develop bioenergy. In this regard, bundling orders through coordination strategies could overcome the challenges and improve supply chain efficiency. As such, there is a need to investigate the impact of coordination strategies on the supply chain and players' performance.

The main goal of this study was to enhance the level of biomass-based energy production in remote communities in a cost-efficient manner by incorporating coordination strategies into the biomass supply chain. In doing so, a simulation-optimization model was developed to formulate and compare cost-sharing, quantity discounts, and no coordination scenarios with respect to minimizing the total cost of the biomass supply chain. The model was then applied to a case study in Canada's off-grid northern communities. In this case study, wood pellets were supposed to generate electricity as an alternative for diesel. The impact of the three mentioned scenarios on players' and supply chain's cost performance as well as share of biomass in generating energy were investigated.

This research presented a simulation-based optimization model to incorporate coordination scenarios in a biomass supply chain, including suppliers, hubs, and end-users. Using system dynamics, we developed a model to simulate the quantity discount, cost-sharing, and no coordination scenarios. Accordingly, the optimal decisions have been made over time with the objective of minimizing the total cost of the supply chain under each scenario. This cost consists of purchase, storage, and delivery costs as well as the costs of electricity generation from biomass and diesel throughout a time horizon of 12 months. The models were applied to the case study, and the optimal decisions on the delivery schedule of biomass, offered prices, cost-sharing ratios, biomass, and diesel conversion facilities' operational plans, as well as inventory levels at hubs and communities, were made. Also, the impact of coordination and no-coordination scenarios on the cost of players' was investigated. Using the case study, it was illustrated that the coordination strategies effectively promoted the scale of biomass orders and thus improved the cost efficiency of hubs and communities. On the basis of case study results, hubs and communities preferred quantity discounts coordination strategy because they benefited more under this scenario compared to cost-sharing strategy while suppliers gained higher cost efficiency from the cost-sharing scenario. In addition, the sensitivity analysis results showed that the cost of hubs and communities were much impacted by biomass price than their storage capacities. In this sense, variations in biomass price, the scale of communities, the number of supply chain players at each stage, and the size of storage capacities changed the players' preferred coordination strategy. However, all players gained higher cost savings as well as biomass-based energy production level under coordination scenarios compared to no coordination scenarios. In this sense, it was concluded that small communities preferred a cost-sharing strategy while using a cheaper type of biomass. Hubs also preferred cost-sharing while using a more expensive type of biomass. On the other hand, storage capacities' size impacted the suppliers' cost more than other factors, and storage variations might change their preference strategy from cost-sharing to quantity discounts.

## 4.2. Research Contribution

In this work, novel dynamic modeling is proposed for comparative analysis of coordination strategies in the biomass supply chain context, focusing on biomass-based energy production for remote communities. The main originalities that correspond to this approach are as follows:

1) Simulated the dynamic complexity of coordination scenarios, including quantity discounts and cost-sharing in remote communities' biomass supply chain using system dynamics modeling.
2) Obtained the optimal supply chain arrangements under quantity discounts and cost-sharing scenarios over time with respect to minimizing total cost of biomass supply chain using the case study in Canada's off-grid northern communities
3) Analyzed the impacts of quantity discounts, cost-sharing, and no coordination strategies on the supply chain characteristics, cost efficiency of players, as well as bioenergy production level over time
4) Analyzed the most efficient coordination scenarios from the perspective of each parties' in various conditions by performing a dynamic comparative analysis

## 4.3. Limitations and Future Work

One limitation of this study is that it focused on the cost-efficiency of integrating coordination strategies in the biomass supply chain of remote communities. Since biomass is a sustainable alternative to fossil fuels, other than economic gains,  social and environmental aspects of sustainability could also be considered to concentrate on social and environmental gains of biomass supply chain coordination strategies in the remote communities [79]. In this sense, a multi-objective model could be formulated to simulate coordination scenarios and optimize the biomass supply chain's environmental and social benefits.

Ash residues, which can be added to several building materials such as cement or used in compost as a fertilizer, could also be considered a biomass source for electricity generation [44].

Inherent uncertainties in biomass-based production chains have a significant influence on coordination effectiveness of the system and could be happened in different phases and activities. Unpredictable changes in the quantity and timing of demand result in demand uncertainty. Consumer demand fluctuations caused by seasonal patterns or variations in end-user preferences. In this regard, efficient demand management strategies are vital to reduce the negative impacts of demand variations on optimal decisions and enhance energy security. Besides, supply uncertainties including variations in raw material quantity and quality as well as changes in supply lead time are due to several reasons such as seasonality of supply, biomass degradation, and bad weather condition [52]. Thus, several sources of uncertainties, such as those in biomass supply and demand could be incorporated into the model of this research.

In addition, other types of coordination strategies such as risk-sharing contracts or contracts integrating more than one strategy could be analyzed.

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# Appendices

Appendix A

Table 1-List of variables and parameters.

| Sets | Definition |
| --- | --- |
| $i$ | Set of suppliers |
| $j$ | Set of communities (end users) |
| $k$ | Set of hubs |
| $t$ | Time (months) |
| **Stock Variables (and units) with Corresponding Players** | |
| Community | |
| $SI_j^{(t)}$: Biomass stock level at community "$j$" at time "$t$"—(kg) | |
| $W^{(T)}$: Cumulative cost of communities at time "$t$"—(CAD) | |
| Hub | |
| $SH_k^{(t)}$: Biomass stock level at hub "$k$" at time "$t$"—(kg) | |
| $V^{(T)}$: Cumulative cost of hubs at time "$t$"—(CAD) | |
| $C^{(T)}$: Cumulative total cost of supply chain at time "$t$"—(CAD) | |
| **Flow Variables (and units) with Corresponding Players** | |
| Community | |
| $w^{(t)}$: Cost of communities at time "$t$"—(CAD/month) | |
| $y_{jk}^{(t)}$: Biomass order by community "$j$" to hub "$k$" at time "$t$"—(kg/month)—Decision variable | |
| $z_j^{(t)}$: Biomass use for electricity production at community "$j$" at time "$t$"—(kg/month) | |
| Hub | |
| $v^{(t)}$: Cost of hubs at time "$t$"—(CAD/month) | |
| $x_{kj}^{(t)}$: Biomass order by hub "$k$" to supplier "$i$" at time "$t$" (kg/month)—Decision variable | |

| |
|---|
| $c^{(t)}$: Total collective cost of supply chain at time "$t$"—(CAD/month) |
| **Auxiliary Variables(and units) with Corresponding Players** |
| Community |
| $Y_{jk}^{(t)}$: Order capacity to hub "$k$" by community "$j$" at time "$t$"—(kg/month) |
| $\Phi_{kj}^{(t)}$: Order ratio to hub "$k$" by community "$j$" at time "$t$"—(Dimensionless) |
| $F_j^{(t)}$: Electricity production from fossil fuel at community "$j$" at time "$t$"—(kWh/month) |
| $B_j^{(t)}$: Electricity production from biomass at community "$j$" at time "$t$"—(kWh/month) |
| $BDC^{(t)}$: Biomass distribution cost to communities at time "$t$"—(CAD/month) |
| $BSC^{(t)}$: Biomass storage cost at communities at time "$t$"—(CAD/month) |
| $f_j^{(t)}$: Electricity production cost from fossil fuel at time "$t$"—(CAD/month) |
| $FEC^{(t)}$: Fossil-based energy generation cost at time "$t$"—(CAD/month) |
| $BCC^{(t)}$: Biomass-to-electricity conversion cost at time "$t$"—(CAD/month) |
| $\alpha_{jk}^{m}$: Maximum cost sharing ratio of community "$j$" with hub "$k$"—(Dimensionless)—Decision variable |
| $\alpha_{jk}^{(t)}$: Cost sharing ratio of community "$j$" with hub "$k$" at time "$t$"—(Dimensionless)—Decision variable |
| Hub |
| $X_{ki}^{(t)}$: Order capacity to supplier "$i$" by hub "$k$" at time "$t$"—(kg/month) |
| $\delta_{ki}^{(t)}$: Order ratio to supplier "$i$" by hub "$k$" at time "$t$"—(Dimensionless) |
| $R_{kj}^{(t)}$: Biomass price offered by hub "$k$" to community "$j$" including delivery at time "$t$"—(CAD/kg)—Decision variable |
| $BPC^{(t)}$: Biomass purchasing cost at time "$t$"—(CAD/month) |
| $BSH^{(t)}$: Biomass storage cost at hubs at time "$t$"—(CAD/month) |
| $\alpha_{ki}^{m}$: Maximum cost sharing ratio of hub "$k$" with supplier "$i$"—(Dimensionless)—Decision variable |
| $\alpha_{ki}^{(t)}$: Cost sharing ratio of hub "$k$" with supplier "$i$" at time "$t$"—(Dimensionless)—Decision |

| |
|---|
| variable |
| $CSH^{(t)}$: Communities' cost shared with hubs at time "$t$"—(CAD/month) |
| Supplier |
| $P_{ik}^{(t)}$: Biomass price offered by supplier "$i$" to hub "$k$" including delivery at time "t"—(CAD/kg)—Decision variable |
| $HCS^{(t)}$: Hubs' cost shared with suppliers at time "$t$"—(CAD/month) |
| **Constant Variables (and units) with Corresponding Players** |
| Community |
| $I_j$: Capacity of biomass storage at community "$j$"—(kg) |
| $E_j$: Capacity of biomass-to-electricity conversion facility at community "$j$"—(kW) |
| $D_j^{(t)}$: Electricity demand in community "$j$" at time "$t$"—(kWh/month) |
| $\varepsilon_j$: Loading factor of biomass-to-electricity conversion facility at community "$j$"—(Dimensionless) |
| $G_j$: holding cost at community "$j$" per unit of time—(CAD/kg) |
| $\delta_j^{(t)}$: Levelized electricity generation cost from diesel at community "$j$"—(CAD/kWh) |
| $\gamma_j$: Levelized biomass-to-electricity conversion cost at community "$j$"—(CAD/kWh) |
| $\beta_j$: Biomass conversion ratio in community "$j$"—(kWh/kg) |
| $wh_j$: Working hours per day—(h) |
| $wd_j$: Working days—(day) |
| $ts_j$: Time scale—(h) |
| Hub |
| $L_k$: Holding cost at hub "$k$" per unit of time—(CAD/kg) |
| $H_k$: Capacity of hub "$k$"—(kg) |
| $R_k^u$: Biomass price of hub "$k$" (including delivery) without discount—(CAD/kg) |
| $R_k^l$: Biomass price of hub "$k$" (including delivery) with full discount—(CAD/kg) |

| Supplier |
|---|
| $S_i$: Biomass supply capacity of supplier "$i$"—(kg) |
| $P_i^l$: Biomass price of supplier "$i$" with full discount—(CAD/kg) |
| $P_i^u$: Biomass price of supplier "$i$" with no discount—(CAD/kg) |

**A Description of the Equations and Variables of Quantity Discount Strategy Defined in Vensim Platform:**

(1) Biomass stock at hub [hub] = INTEG (SUM (Biomass order by hub to supplier [supplier!, hub])-SUM(Biomass order by community to hub[hub, community!]))

(2) Biomass stock at community [community] = INTEG (SUM (Biomass order by community to hub [hub!, Community])-Biomass use for electricity production at community[community]

(3) Biomass order by hub to supplier[supplier, hub]= IF THEN ELSE(Time=3:OR:Time=4:OR:Time=5:OR:Time=6, Proportional delivery ratio of supplier to Biomass order by hub to supplier[supplier, hub]= hub[supplier, hub]*Order capacity to supplier[supplier, hub], 0 )

(4) Biomass order by community to hub[hubs, communities]= IF THEN ELSE( Time=3:OR:Time=4:OR:Time=5:OR:Time=6:OR:Time=7:OR:Time=8, Order capacity by community to hub[hub, community]*Proportional delivery ratio of hub to community[hub, community] , 0 )

(5) Biomass use for electricity production at community[community]= max(min((min((Time scale*Capacity of biomass to electricity conversion facility[community]*Loading factor of biomass to electricity conversion facility[community]),Electricity demand[community])/Biomass conversion rate[community]),Biomass stock at community[community]/TIME STEP),0)

(6) Proportional delivery ratio of supplier to hub [supplier, hub] = Order ratio to suppliers [supplier, hubs]/Total delivery ratio of suppliers [supplier]

(7) Total delivery ratio of supplier [supplier] = SUM (Order ratio to supplier [supplier, hub!])

(8) 0<=Order ratio to supplier [supplier, hub] <=1

(9) Initial value of order ratio to supplier [supplier, hub] =1

(10) Order capacity to supplier [supplier, hub] = max (min ((Capacity of hub [hub]-Biomass stock at hub [hub])/TIME STEP, Supplier capacity [supplier]), 0)

(11) Capacity of hub [hub] = 350000, 400000

(12) Supplier capacity [supplier] = 33300, 34000, 34700, 37000, 35000, 34000

(13) Total biomass purchase cost of hub [hub] = SUM (Biomass purchase cost [hub, supplier!])

(14) Biomass purchase cost [hub, supplier] = Biomass price offered by supplier [supplier, hub]*Biomass order by hub to supplier [supplier, hub]

(15) Biomass price offered by supplier [supplier, hub] = Biomass price of supplier with no discount [supplier] - (Biomass price of supplier with no discount [supplier]-Biomass price of supplier with full discount [Supplier])*((Biomass order by hub to supplier [supplier, hub])/Supplier capacity [supplier])

(16) Biomass price of supplier with no discount [supplier] = 0.205, 0.21, 0.2, 0.215, 0.22, 0.22

(17) Biomass storage cost at hub [hub] = (Biomass stock at hub [hub]*Holding cost at hub per unit of time [hub])/TIME STEP

(18) Holding cost at hub per unit of time [hub] = 0.002, 0.0015

(19) Proportional delivery ratio of hub to community [hub, community] = Order ratio to hub [hub, community]/Total delivery ratio of hub [hub]

(20) Total delivery ratio of hub [hub] = SUM (Order ratio to hub [hub, community!])

(21) 0<=Order ratio to hub [hub, community] <=1

(22) Initial value of Order ratio to hub [hub, community=1

(23) Order capacity by community to hub [hub, community] = max (min ((Capacity of biomass storage at community [community]-Biomass stock at community [Community]), Biomass stock at hub [hub]), 0)/TIME STEP

(24) Capacity of biomass storage at community [community] = 200000, 200000, $1.5\times10^6$

(25) Biomass distribution cost to community [community] = SUM (Biomass distribution cost from hub to community [hub!, community])

(26) Biomass distribution cost from hub to community [hub, community] = (Biomass price offered by hub [hub, community]*Biomass order by community to hub [hub, community])

(27) Biomass price offered by hub [hub, community] = Biomass price of hub with no discount [hub]-(Biomass price of hub with no discount [hub]-Biomass price of hub with full discount [hub])*(Biomass order by community to hub [hub, community]/ (Capacity of hub [hub]/TIME STEP))

(28) Biomass price of hub with full discount [hub] = 0.235, 0.266

(29) Biomass price of hub with no discount [hub] = 0.362, 0.409

(30) Biomass storage cost at community [community] = (Biomass stock at community [community]*Holding cost at community [community])/TIME STEP

(31) Electricity production cost from biomass [community] = Electricity production from biomass [community]*Levelized biomass to electricity conversion cost [community]

(32) Electricity production cost from fossil fuel [community] = Electricity production from fossil fuel [community]*Levelized electricity generation cost from diesel [community]

(33) Electricity production from biomass [community] = Biomass conversion rate [community]*Biomass use for electricity production at community [community]*Loading factor of biomass to electricity conversion facility [community]

(34) Electricity production from fossil fuel [community] = Electricity demand [community]-Electricity production from biomass [community]

(35) Cumulative cost of hubs= INTEG (SUM (Cost of hubs [hub!]))

(36) Initial value=0

(37) Cumulative cost of communities= SUM (Cost of communities [community!])

(38) Initial value=0

(39) Total collective cost of supply chain = SUM (Cost of communities [community!])+SUM (Cost of hubs [hub!])

(40) Cumulative total cost= INTEG (Total collective cost of supply chain)

(41) Levelized biomass to electricity conversion cost [community] = 0.046, 0.044, 0.048

(42) Levelized electricity generation cost from diesel [community] = 0.208, 0.215, 0.207

(43) Biomass conversion rate [community] = 4.7, 4.8, 4.6

(44) Capacity of biomass to electricity conversion facility [community] = 500, 500, 500

(45) Working days= 30

(46) Hours= 24

(47) TIME STEP= 1

**A Description of the Equations and Variables of Cost Sharing Strategy Defined in Vensim Platform:**

(1) Biomass stock at hub [hub] = INTEG (SUM (Biomass order by hub to supplier [supplier!, hub])-SUM(Biomass order by community to hub[hub, community!]))

(2) Biomass stock at community [community] = INTEG (SUM (Biomass order by community to hub [hub!, Community])-Biomass use for electricity production at community[community]

(3) Biomass order by hub to supplier[supplier, hub]= IF THEN ELSE(Time=3:OR:Time=4:OR:Time=5:OR:Time=6, proportional delivery ratio of supplier to hub[supplier, hub]*Order capacity to supplier[supplier, hub], 0 )

(4) Biomass order by community to hub[hub, community]= IF THEN ELSE( Time=3:OR:Time=4:OR:Time=5:OR:Time=6:OR:Time=7:OR:Time=8, Order capacity by community to hub[hub, community]*proportional delivery ratio of hub to community[hub, community] , 0 )

(5) Biomass use for electricity production at community [community] = SUM (Biomass order by community to hub [hub!, community])-Biomass use for electricity production at community[community]

(6) Proportional delivery ratio of supplier to hub [suppliers, hubs] = Order ratio to suppliers [supplier, hubs]/Total delivery ratio of suppliers [supplier]

(7) Total delivery ratio of supplier [supplier] = SUM (Order ratio to supplier [supplier, hub!])

(8) 0<=Order ratio to supplier [supplier, hub] <=1

(9) Initial value of order ratio to supplier [supplier, hub] =1

(10) Order capacity to supplier [supplier, hub] = max (min ((Capacity of hub [hub]-Biomass stock at hub [hub])/TIME STEP, Supplier capacity [supplier]), 0)

(11) Capacity of hub [hub] = 350000, 400000

(12) Supplier capacity [supplier] = 33300, 34000, 34700, 37000, 35000, 34000

(13) Total biomass purchase cost of hub [hub] = SUM (Biomass purchase cost [hub, supplier!])

(14) Biomass purchase cost [hub, supplier] = Biomass price offered by supplier [supplier]*Biomass order by hub to supplier [supplier, hub]

(15) Biomass price offered by supplier [supplier] = 0.205, 0.21, 0.2, 0.215, 0.22, 0.22

(16) Biomass storage cost at hub [hub] = (Biomass stock at hub [hub]*Holding cost at hub per unit of time [hub])/TIME STEP

(17) Holding cost at hub per unit of time [hub] = 0.002, 0.0015

(18) Cost of hubs could be shared with suppliers [hub] = Biomass storage cost at hub [hub] +Total biomass purchase cost of hub [hub]

(19) Hubs' cost shared with suppliers [hub, supplier] = Cost of hubs could be shared with suppliers [hub]*Cost sharing ratio between Hub and supplier [hub, supplier]

(20) Cost sharing ratio between Hub and supplier [hub, supplier] = Maximum cost sharing ratio between Hub [hub]*(Biomass order by hub to supplier [supplier, hub]/Supplier capacity [supplier])

(21) 0<=Maximum cost sharing ratio between Hub [hub] <=1

(22) Initial value in the model = 0

(23) Proportional delivery ratio of hub to community [hub, community] = Order ratio to hub [hub, community]/Total delivery ratio of hub [hub]

(24) Total delivery ratio of hub [hub] = SUM (Order ratio to hub [hub, community!])

(25) 0<=Order ratio to hub [hub, community] <=1

(26) Initial value of Order ratio to hub [hub, community=1

(27) Order capacity by community to hub [hub, community] = max (min ((Capacity of biomass storage at community [community]-Biomass stock at community [Community]), Biomass stock at hub [hub]), 0)/TIME STEP

(28) Capacity of biomass storage at community [community] = 200,000, 200,000, $1.5\times 10^6$

(29) Biomass distribution cost to community [community] = SUM (Biomass distribution cost from hub to community [hub!, community])

(30) Biomass distribution cost from hub to community [hub, community] = (Biomass price offered by hub [hub, community]*Biomass order by community to hub [hub, community])

(31) Biomass price offered by hub [hub] = 0.362, 0.409

(32) Biomass storage cost at community [community] = (Biomass stock at community [community]*Holding cost at community [community])/TIME STEP

(33) Electricity production cost from biomass [community] = Electricity production from biomass [community]*Levelized biomass to electricity conversion cost [community]

(34) Electricity production cost from fossil fuel [community] = Electricity production from fossil fuel [community]*Levelized electricity generation cost from diesel [community]

(35) Electricity production from biomass [community] = Biomass conversion rate [community]*Biomass use for electricity production at community [community]*Loading factor of biomass to electricity conversion facility [community]

(36) Electricity production from fossil fuel [community] = Electricity demand [community]-Electricity production from biomass [community]

(37) Cost of communities could be shared with hubs[community] = Biomass distribution cost to community[community]+Biomass storage cost at community[community]+Electricity production cost from biomass[community]+Electricity production cost from fossil fuel[community]

(38) Cost of communities could be shared with hubs[community] = Biomass distribution cost to community[community]+Biomass storage cost at community[community]+Electricity production cost from biomass[community]+Electricity production cost from fossil fuel[community]

(39) Communities' cost shared with hubs [community, hub] = Cost of communities could be shared with hubs [community]*Cost sharing ratio between community and hub [community, hub]

(40) Cost sharing ratio between community and hub [community, hub] = (Biomass order by community to hub [hub, community]/Capacity of hub [hub])*Maximum cost sharing ratio between community and hub [community]*Time

(41) 0<=Maximum cost sharing ratio between community and hub [community] <=1

(42) Initial value of cost sharing ratio between community and hub [community] = 0

(43) Cost of hubs[hub] = Total biomass purchase cost of hub[hub]+Biomass storage cost at hub[hub]+SUM( Communities' cost shared with hubs[community!, hub] )-SUM( Hubs' cost shared with suppliers[hub, supplier!] )

(44) Cumulative cost of hubs = INTEG (SUM (Cost of hubs [hub!]))

(45) Cost of communities [community] = Biomass distribution cost to community[community]+Electricity production cost from biomass[community]+Electricity production cost from fossil fuel[community]+Biomass storage cost at community[community]-SUM( Communities' cost shared with hubs[community, hub!] )

(46) Cumulative cost of communities = INTEG [SUM (Cost of communities [community!])]

(47) Total collective cost of supply chain = SUM (Cost of communities [community!])+SUM (Cost of hubs [hub!])+SUM (Hubs' cost shared with suppliers [hub!, supplier!])

(48) Cumulative total collective cost = INTEG (Total collective cost of supply chain)

(49) Initial value= 0

(50) Levelized biomass to electricity conversion cost [community] = 0.046, 0.044, 0.048

(51) Levelized electricity generation cost from diesel [community] = 0.208, 0.215, 0.207

(52) Biomass conversion rate [community] = 4.7, 4.8, 4.6

(53) Capacity of biomass to electricity conversion facility [community] = 500, 500, 500

(54) Working days= 30

(55) Hours= 24

(56) TIME STEP= 1