PROFIT ALLOCATION IN COLLABORATIVE BIO-ENERGY AND BIO-FUEL SUPPLY CHAINS

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Abstract

Forest-based biomass is an important renewable source for generating bio-energy and bio-fuels, while it has high feedstock costs and a complex supply chain. Therefore, many previous studies focused on optimizing forest-based biomass supply chains to improve its competitiveness. The main question after optimization is the allocation of benefits among supply chain entities. Allocation based on game theory methods can be useful and has been used on collaboration in transportation activities in forestry, but allocation of benefits to individual participants in forest-based biomass supply chains has not been done before. This thesis addresses this gap using concepts of game theory. A case involving three bio-product conversion plants (denoted as plant A,B,C) in British Columbia is studied, and collaboration among plants is defined as the exchange of sawmill residues. An optimization model is presented to determine biomass flow and technology type at each plant, with the goal of maximizing the net present value of the total profit. The results indicate the collaboration would generate $61 million, which is more profitable than plants operating individually. To distribute the total profit, a number of allocation methods are investigated, including the Shapley value, the nucleolus, proportional methods, methods based on separable and non-separable costs (ECM, ACAM, CGM), and the equal profit method (EPM). The comparison of methods reveals that the Shapley value, the nucleolus, ACAM, and CGM generate similar stable results in which plant A, B, and C could save 0.2%, 3.7%, and 620%, respectively, while EPM gives a different stable allocation, where the relative saving reduces to 7% for plant C, and increases to 0.4% and 7% for plant A and B. The relative saving obtained by plants is also investigated through revenue and cost break-down analysis, which shows plant A and C make the largest portion of profit by selling bio-fuel, and plant B is highly dependent on the sales of sawmill residues. Furthermore, a sensitivity analysis is conducted to evaluate the impact of changes in biomass availability, biomass costs, bio-product demand, bio-product prices, and discount rate. It is observed the profitability of collaboration is closely related to the market situation of bio-oil.

Lay summary

Biomass is the second largest contributor in Canada's renewable energy production, and its utilization and profitability can be further improved by the collaboration among supply chain partners. The stability of collaboration, however, closely relies on whether the total profit can be properly shared. Therefore, it is important to find a profit allocation plan that can satisfy all partners. This thesis reviews a number of allocation methods which are developed based on game theory and have been proposed in previous literature, and evaluates the fairness of these methods with a case study involving three bio-energy and bio-fuel conversion plants in British Columbia. This thesis also assesses the impact of fluctuations in biomass availability, biomass costs, bio-product demand, bio-product prices, and discount rate on the collaboration. The results of this study indicate that the collaboration of the three conversion plants is most sensitive to the market price of bio-oil.

Preface

All the work presented in this thesis was carried out by the author, Yi Gao, during her Master's degree program, under the supervision of Dr. Taraneh Sowlati, at the Industrial Engineering Research Group of the University of British Columbia, Vancouver, BC. Dr. Sowlati provided advice and comments on defining the research problem and objectives, developing and validating the model, analyzing the results, and writing the thesis.

The optimization model used in Chapter 3 was adopted from the work presented in Akhtari, Sowlati, & Griess (2018). The model, however, was modified by the author in order to incorporate the consideration of different collaboration that can be formed in the case study.

A manuscript has been prepared based on this research and is ready for submission to a refereed journal: Gao Y., & Sowlati T. Profit allocation in collaborative bio-energy and bio-fuel supply chains.

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In memory of my grandfather. It has been eight years since I told you I was going to university, and now I have finally made it.

Chapter 1: Introduction

1.1 Background

1.1.1 Bio-energy and bio-fuel in Canada

Renewable energy accounts for about 17% of Canada's total energy supply, while the various forms of renewable energy have different share. Biomass, as one of the main sources, makes up around 23% in Canada's renewable energy production and is the second largest renewable source after hydro (Natural Resources Canada, 2018b).

Biomass can be transformed into solid, liquid or gaseous energy using different conversion technologies including combustion, gasification, pyrolysis, and other biochemical methods. Among all conversion technologies, combustion is the most developed ones and converts biomass into heat, mechanical power, or electricity using excess oxygen during the process (McKendry, 2002a). It is suitable for any type of biomass, but practically it only accepts biomass with a moisture content under 50% on a wet basis (Koppejan & Loo, 2007). The efficiency of combustion technologies varies considerably from 50% to 90% (Siemons & Quaak, 1996). Gasification converts biomass into combustible gas mixture in an oxygen-starved environment. Compared to combustion, gasification has more stringent requirements on feedstock quality: 1) the biomass moisture content should be below 10-15%; 2) the ash content should be below 5% to prevent clinker; and 3) the particle size should be typically 10%-20% of the hearth diameter (McKendry, 2002b). As the result of better feedstock quality and less heat loss from internal energy exchange, gasification tends to have a higher conversion efficiency than combustion on average, estimated at 80-87% (Prins, 2005). Pyrolysis is another thermochemical process happening in an oxygen-absent environment. It has a very complex reaction scheme with over 100 intermediate products, while the final products are mainly bio-oil, charcoal, and combustible gas (Demirbas & Balat, 2007). The conversion of biomass to bio-oil has an estimated efficiency of up to 70%, which is challenged by problems such as poor thermal stability and corrosivity of the oil (Demirbas & Balat, 2007).

In recent years, the Canadian bio-energy sector has seen a growth in both bio-power and bio-heat generation. More specifically, Canada had 70 bio-power plants with a total installed capacity of 2,043 megawatts in 2014 (Natural Resources Canada, 2017a), and the production expanded to 135 plants with a total capacity of approximately 3,000 megawatts by the end of 2016 (Macleod et al., 2018). As for bio-heat, there were 282 conversion facilities in Canada in 2016, since then it experienced an increase of 32% and as of March 2017, the Canadian Bioheat Database showed there were 364 bio-heat projects in operation, which largely served public institutions such as schools and hospitals (Stephen, Blair, & Mabee, 2017).

In addition to bio-power and bio-heat, solid and liquid bio-fuels also contribute to diversify the use of biomass. Solid bio-fuels such as wood pellets are produced from biomass through drying and densifying in order to achieve better physical and chemical properties (Natural Resources Canada, 2016). Since 2000, the production of wood pellets in Canada has been increasing (Natural Resources Canada, 2018b), and by the end of 2016 there were 42 plants that were capable of producing 4 million tonnes of wood pellets per year (Macleod et al., 2018).

Liquid bio-fuels can refer to different products according to feedstock and conversion technology. When lignocellulosic biomass such as woody residues are processed through biochemical or thermochemical routes, the liquid bio-fuel products include bio-ethanol, bio-methanol, and pyrolysis bio-oil (Ballesteros & Manzanares, 2019). Canada accounted for 2% of the global liquid bio-fuel production in 2017, and was the 5^{th} largest producer after the United States, Brazil, the European Union and China (Natural Resources Canada, 2018b). Among all liquid bio-fuels, pyrolysis bio-oil (or bio-oil) shows distinct advantages as it can be further processed into transportation fuels such as diesel and gasoline (Sharma, Shinde, Pareek, & Zhang, 2015). However, when it comes to the real application and commercialization of bio-oil, concerns regarding its fuel properties, combustion characteristics and emissions are raised, and studies on its compatibility with gas turbines are limited (Enagi, Al-attab, & Zainal, 2018). Moreover, liquid bio-fuel conversion can only flourish if technological breakthroughs could be realized to improve biomass carbon utilization, to enlarge scale of production, and to reduce investment and production costs (Ballesteros & Manzanares, 2019).

One observation can be made from Canadian bio-energy and bio-fuel markets is that most conversion facilities are based in provinces with rich forestry resources and active forest industries, such as Ontario and British Columbia (Canadian Biomass, 2018; Natural Resources Canada, 2017b; Roach & Berch, 2014; Stephen et al., 2017). According to Bradley (2010), Ontario has the largest renewable bio-energy production capacity, largely from cogeneration at pulp mills and independent power producers, followed by British Columbia and New Brunswick (Table 1-1).

Table 1-1 Canadian bio-energy production capacity by province
(Derived from Bradley, 2010)

Provinces and territories	Bio-energy production capacity (megawatts)
Ontario	2,021
British Columbia	1,601
New Brunswick	437
Alberta	276
Quebec	267
Saskatchewan	246
Nunavut and Northwest Territories	167
Manitoba	35
Prince Edward Island	2
Newfoundland and Labrador	0
Yukon	0
Nova Scotia	0
Total	5,051

More recent data in (Bradburn, 2014) show that British Columbia (BC) has 14 pulp and paper mills with a total of 726.5 megawatts cogeneration capacity to produce bio-heat and bio-power needed for mill operations, accounting for 46% of the total national capacity. BC is also home to 8 independent bio-heat and bio-power producers, the combined capacity of which is 138.3 megawatt electrical and 147.8 megawatt thermal. Besides, BC is a leader in bio-heat district heating, reporting 30 district heating systems in operation, 4 under construction, and 20 in various planning stages. Half of the district heating systems in BC are fueled by wood pellets, as BC dominates wood pellet production with over 2 million tonnes of capacity, 61% of Canada's overall capacity. The pellet plants in BC have an average size of about 180,000 tonnes, which are built mainly for large export markets. Figure 1-1 adopted from (Ministry of Energy, Mines & Petroleum Resources, 2009) exhibits the locations of a part of existing bio-energy and bio-fuel facilities in BC.

Figure 1-1 Existing bio-energy and bio-fuel facilities in BC

(Adopted from Mines and Petroleum Resources, 2009)

1.1.2 Forest-based biomass

The forest industry plays an important role in the Canadian economy (Natural Resources Canada, 2019), contributing $24.6 billion to the nominal gross domestic product (GDP) in 2017 (Natural Resources Canada, 2018a). In addition to the main forest products, there is a large quantity of forest-based biomass that can be used to provide a sustainable supply of bio-based renewable energy (Wood & Layzell, 2003).

Forest-based biomass mainly includes forest residues and wood processing residues (Sowlati, 2016). Forest residues can refer to both logging residues such as non-merchantable stems, tops and branches, and silvicultural residues which are derived from undersized trees during pre-commercial thinning operations. Wood processing residues are produced at sawmills, pulp mills and other wood processing facilities in the forms of sawdust, shavings, bark, hogfuel and wood chips. In addition to forest residues and wood processing residues, fast-growing tree plantations, construction and demolition wastes, and trees killed by natural disturbances such as insects and fires are also considered as forest-based biomass sources (Sowlati, 2016).

BC has the largest forest industry in Canada, acting as a strong driving force for provincial economic and social developments (Ministry of Forests, Lands and Natural Resource Operations, 2016b). According to (Natural Resources Canada, 2018c), in 2016, about 66.4 million cubic meters of merchantable roundwood over 183,778 hectares of harvesting area were harvested in BC, which accounted for approximately 42% of Canada’s annual harvest volume. The total GDP generated by the forest industry was estimated at about $12.94 billion (PwC, 2017), contributing to around 5% of BC’s provincial GDP. Apart from the economic benefits, the forest industry also provided close to 141,000 direct, indirect, and induced job opportunities, with 140 communities now being forest dependent that perform intensive logging practices, road clearing, and other forestry activities (PwC, 2017). The sustainable forestry operations produce a large amount of forest residues, the maximum annual volume of which was estimated to be around 13 million oven dry tonnes (odt) and was enough to meet about 21% of the province’s annual fossil energy demand (Bradley, 2010).

Moreover, the mountain pine beetle (MPB) outbreak in BC has necessitated the use of beetle-killed wood. Since early 2000s, the massive MPB infestation due to mild winters and monoculture resulted in a loss of millions of hectares of pine forest, leaving a considerable amount of residues and unusable dead trees. There is an opportunity to utilize about 11 million odt of MPB-killed stands for the next 20 years, which is sufficient to substitute another 19% of the provincial fossil energy demand (Ralevic & Layzell, 2006). Finally, yet importantly, the production of lumber is accompanied by sawmill residues in the forms of wood chips, sawdust, shavings, and hog fuel. Ghafghazi et al. (2017) anticipated that in 2013, after meeting the demand of secondary forestry sector that produced pulp and paper, OSB, particleboard, MDF, wood pellets, and biomass-based power, there was still about 0.6 million odt of sawmill residues remained untapped in BC.

Although BC has rich forest resources, wildfires have greatly impacted their availability (BC Wildfire Service, 2017), especially in recent years. Summers of 2017 and 2018 are among the two worst wildfire seasons in BC's history, with over 1.2 million hectares burned each year (Wildfire Service, 2018, 2019). As a consequence, it is projected that in the short term the focus of logging should shift to the salvage of damaged timber to make up for the current allowable annual cut, while in the medium term the harvest level will reduce inevitably, putting stress on timber supply in the wildfire affected areas (Forest Analysis and Inventory Branch, 2018).

To mitigate fire hazards, the wood residues in BC were largely burned historically. However, this traditional method is challenged by the concerns over energy waste and air pollution. Furthermore, demand for wood residues is increasing from both primary and secondary users (Spencer & Roeser, 2017). Compared to conventional fossil fuels, forest-based biomass has distinct advantages, namely the potential to mitigate climate change, the ability to secure energy supply, and the possibility to boost local economy, especially in forest-rich communities (Wood & Layzell, 2003). Therefore, in order to promote the use of forest-based biomass, the BC government has issued a series of energy strategies, policies, and initiatives. In 2007, the BC Energy Plan was released with the focus on building a strong and sustainable bio-energy sector, especially by converting MPB affected timber to wood pellets and feedstock for electricity generation and cogeneration (BC Government, 2007). The BC Bio-energy Strategy published in 2008 highlighted $25 million funding to support the development of BC bio-energy projects and technologies (Ministry of Energy, Mines & Petroleum Resources, 2009). Owing to these efforts, BC has established a provincial bio-energy network, with quite few companies using wood residues to generate power for internal use or for use by BC Hydro, and some facilities using wood residues for pellet production (Roach & Berch, 2014). Additionally, the BC government has been developing the Forest Fiber Action Plan to better manage the fiber after primary harvesting and to improve the utilization and value from wood residues (Ministry of Forests, Lands and Natural Resource Operations, 2015). The importance of wood fiber recovery is further addressed in BC's Climate Leadership Plan, with the aim to build a clean economy and reduce annual carbon emissions by up to 25 million tonnes by 2050 (Ministry of Environment & Climate Change Strategy, 2016). BC Forest Carbon Initiative (Ministry of Forests, Lands and Natural Resource Operations, 2016a) recommends turning wood fiber to bio-energy and establishing rural bio-energy facilities as it contributes to local economic development and employment.

That being said, the long-term success of bio-energy and bio-fuel facilities and the utilization of forest-based biomass may still be hindered by some technical and economic barriers in the supply chain. For example, biomass scattered distribution, relatively low energy density and high moisture may cause a strict requirement on equipment and a high cost of collection and transportation. Moreover, due to the nature of the industry, the availability of forest-based biomass is closely dependent on the weather conditions and policy changes, which affects its pricing from time to time (Caputo, Palumbo, Pelagagge, & Scacchia, 2005; Kanzian, Holzleitner, Stampfer, & Ashton, 2009; Shabani, Akhtari, & Sowlati, 2013). In addition, as forest-based biomass can be used in other sectors such as pulp and paper, the competition from other end users will complicate the state of the market. Overall, the variation and uncertainty in the location, quantity, and quality of forest-based biomass have a great impact on the profitability of the supply chain, which could challenge its competitiveness against other energy sources (Shabani et al., 2013). Therefore, proper estimation of biomass supply chain costs is important to facilitate investment decisions.

Several studies have evaluated the costs related to energy and fuel generation using biomass. Cormier (2010) reported that the delivered costs of biomass could account for 45%-60% of the total energy generation cost, with biomass transportation costs being the primary component. Gonzalez et al. (2011) showed that the delivered cost of forest-based biomass was around 70 US dollars per dry ton, lower than that of agricultural biomass. Searcy, Flynn, Ghafoori, & Kumar, (2007) analyzed the costs of transporting biomass and transporting bio-ethanol, showing that transporting bio-ethanol was much more economical than transporting biomass, while at 500 km the cost of transporting biomass by truck was very close to the current wholesale price of natural gas in North America. Dornburg & Faaij (2001) agreed that the biomass costs had the largest impact on the total energy generation cost, and they also pointed out that the scale of biomass energy systems had a positive and significant effect on the systems' economic performance. Some studies compared biomass with other fuel types. For example, Wahlund & Yan (2004) analyzed the costs of a number of bio-energy and bio-fuel production options and concluded that among all alternatives the production of wood pellets for coal substitution could give the highest potential and lowest cost for carbon emission reduction. Gan & Smith (2006) compared the electricity generation costs of forest-based biomass and coal, and their results indicated that forest-based biomass would be preferable if emission reduction targets were established and carbon taxes were in effect. In all of these studies, however, the estimated costs of bio-energy and bio-fuel production might not be the lowest possible, as the studied biomass supply chain was not optimized.

Mathematical modelling and optimization have been extensively used to design the optimal biomass supply chains and to improve the competitiveness of forest-based biomass for bio-energy and bio-fuel production. A number of studies focused on the strategic decisions regarding plant locations and capacities (Freppaz et al., 2004; F. Frombo, Minciardi, Robba, Rosso, & Sacile, 2009; Francesco Frombo, Minciardi, Robba, & Sacile, 2009; Natarajan, Leduc, Pelkonen, Tomppo, & Dotzauer, 2014; Schmidt, Leduc, Dotzauer, Kindermann, &

Schmid, 2010). Others such as Gunnarsson, Rönnqvist, & Lundgren (2004) and Kanzian et al. (2009) determined the flow of biomass and decided when and where the biomass should be harvested, transported, stored and converted into bio-products. Several studies combined different planning levels. For example, Alex Marvin, Schmidt, Benjaafar, Tiffany, & Daoutidis (2012) and Lin, Rodríguez, Shastri, Hansen, & Ting (2014) presented optimization models to simultaneously determine the locations and capacities of bio-fuel facilities, and biomass harvest and distribution. However, these previous studies only aimed at optimizing the entire supply chain to achieve the lowest cost or highest gain, while it is not clear how the total profit should be shared when multiple supply chain partners are participating and collaborating.

1.2 Collaboration and game theory

The collaboration between companies is usually established by exchanging information and resources, sharing risks and rewards, and planning jointly (Simatupang & Sridharan, 2005). As a result of successful collaboration, companies can benefit from improved profitability and ability to satisfy customers. Moreover, for forest companies, a well-managed collaboration could also facilitate the entry to new markets and the diversification of product portfolio (Piltan & Sowlati, 2014; Simatupang & Sridharan, 2005). On the other hand, establishing collaborations requires much time and effort, and the performance of collaborations largely depends on the similarities, compatibilities, and mutual trust among partners (Piltan, Sowlati, Cohen, Gaston, & Kozak, 2015). An obstacle to successful collaborations is identified to be the lack of agreement on the cost or benefit sharing (Narayanan & Raman, 2004). Without a fair sharing, companies have no incentive to participate even if the overall collaboration is beneficial (Katok & Pavlov, 2013). Therefore, it necessitates a suitable mechanism that can properly distribute the cost or benefits of the collaboration among the partners, and models based on game theory could be developed to deal with this problem (Lehoux, D’amours, Frein, Langevin, & Penz, 2011).

Game theory is defined as the study of mathematical models of conflict and cooperation among rational decision makers (Myerson, 2013). There have been some applications of using game theory for cost allocation in forestry. For example, Audy, D’Amours, & Rönnqvist (2007) studied a wood fiber flow collaboration under the leadership of one customer whose objective was to maximize its own payoff, and therefore the collaboration could not gain all the attainable benefits. Similar case studies conducted with furniture companies and forest companies by other researchers (Audy & D'Amours, 2008; Audy, D'Amours, & Rönnqvist, 2012) proved that the leadership could provide better return for companies, and it was usually taken by the company with the highest shipping volume. Frisk, Göthe-Lundgren, Jörnsten, & Rönnqvist (2010) proposed a new cost allocation method and managed to evenly distribute savings to satisfy every forest company in the collaboration. Audy, D 'amours, & Rousseau (2011) added more constraints to this method in order to consider the minimum saving percentage that might be insisted by some companies, and to reward the flexibility in collaborative furniture transportation planning. Flisberg, Frisk, Onnqvist, & Guajardo (2015) also modified this method to ease the computational process for a country-wide case study that involved 61 forest transportation companies with more than 6.1 million tons of biomass.

The literature related to other sectors has diversified the utilization of game theory in real life case studies including the collaborative project development in water resource management and service expansion in the power industry. A study incorporating game theory concepts in natural resource management is done by Straffin & Heaney (1981). In this paper, the authors planned water resource development projects to serve the purposes of navigation improvement, flood control, and power generation. The budget for different purposes was determined using the game theory allocation methods. An example of the cost allocation in the power industry is by Erli et al. (2005). The authors studied the allocation of the power transmission expansion cost among the participants in the electric market who benefited from congestion relief in the power system.

1.3 Research objectives

By summarizing the aforementioned literature, it is noted that unlike other industries where collaboration is concerned with different supply chain activities, in the forestry sector, cost allocation studies are mostly related to optimizing supply chains with collaborative transportation. Nonetheless, when the collaboration is in other forms such as sharing resources, it is not clear that how the optimized total profit should be allocated to each individual participant. To address this gap, this research has four main objectives:

1) Modify an optimization model of the forest-based biomass supply chain to calculate the maximum profit when different participants form the collaboration;
2) Allocate the total optimized profit to individual participants based on different game theory allocation methods;
3) Evaluate the fairness of collaboration and further analyze the desirability of collaboration for each participant.
4) Perform sensitivity analysis to evaluate the sensitivity of optimal results to the changes in the cost and availability of forest-based biomass, the market demand and price of bio-products, and discount rate.

1.4 Case study

In this research, a case involving three communities in interior BC is considered. These communities are either off the grid or challenged by the lack of connection to natural gas pipelines. However, with forestry being the main industry, they have access to a variety of forest-based biomass resources, including sawmill residues and harvesting residues. Moreover, this region has been significantly affected by MPB, which has left a great amount of beetle-killed trees to be salvaged and utilized. Currently, residues from remote and private sawmills in this area are burned or landfilled, and the majority of harvesting residues is left on the ground in the forests and burned. The burning of biomass does not contribute to local economy, but results in many problems like air pollution and carbon emission. In order to address these issues and to better utilize forest-based biomass, the communities show a growing interest in converting them to heat, electricity, and other bio-products. In addition to providing energy at a lower price, establishing biomass conversion facilities also help entering new bio-markets, generating additional incomes, and creating more employment opportunities.

The potential locations for conversion facilities are considered to be at the three sawmills, each sawmill is within each community. The conversion facilities are denoted as plant A, plant B, and plant C in this study. Figure 1.1 shows the general location of the three plants. The sawmill chosen for plant A has the ability to generate approximately 16,150 odt of clean chips and 8,550 odt of hog fuel per year. The sawmill chosen for plant B generates approximately 6,000 odt of sawdust and 1,600 odt of hog fuel annually. The sawmill in plant C has about 1400 odt of clean chips and 1000 odt of hog fuel available per year. These sawmill residues are not committed to other industries, therefore they can be used internally at no additional cost or sold to other conversion facilities.

Figure 1-2 General locations of plant A, plant B, and plant C
(Adopted from Ministry of Forests, Land and Natural Resource Operations, 2018)

The collaboration among plants A, B, and C is assumed to be in terms of exchanging sawmill residues. That is, one plant can buy or sell sawmill residues from/to another plant only if they collaborate. Otherwise, the sawmill residues at each plant are either used internally, burned, or sent to landfill, and the cost of storing, burning or landfilling of residues is not considered. The purchase prices of sawmill residues are estimated to be \$25/odt for clean wood chips and \$10/odt for hogfuel, which are constant regardless of the biomass quality. In addition to sawmill residues, the plants can also buy forest residues and MPB infected logs from cut-blocks. The total purchase and preprocessing cost is about \$25/odt, while it is worth noticing that the delivered cost of these types of biomass really depends on the distance from the cut-blocks to plants, which could vary considerably.

An optimization model is run to determine the type and size of conversion technologies that should be installed at each plant. Once the conversion facility is established, it would be kept in operation throughout the planning horizon (20 years). This reflects the fact that given the high capital costs, it is unreasonable to install a conversion facility and terminates its operation before the end of the planning horizon. The results of the optimization model indicate the optimal NPV that can be generated by the whole supply chain. In order to distribute this NPV among the three plants, different coalitions can be assumed.

Considering different partnerships among the three plants, there are seven possible coalitions as described in Table 1-1. The coalitions labelled as C1, C2, and C3 represent the scenarios that plants do not collaborate with each other, but operate individually, with the analysis focusing on plant A, plant B, and plant C, respectively. C4 is the collaboration between plant A and plant B. Similarly, C5 and C6 are the collaboration between plant A and plant C, and the collaboration between plant B and plant C. Coalitions C1 to C6 are also referred to as sub coalitions, in which some plants are not included. The coalition C7, which includes all three plants, is the so-called grand coalition.

Table 1-2 Possible coalitions formed by different plants

Coalition	Participating plant(s)
C1	Plant A
C2	Plant B
C3	Plant C
C4	Plant A and plant B
C5	Plant A and plant C
C6	Plant B and plant C
C7	Plant A, plant B and plant C

1.5 Thesis structure

This thesis is organized as follows. Chapter 2 introduces the most frequently used cost allocation methods developed from game theory, and presents fairness-related properties that need to be considered when assessing allocations. In addition, this chapter also reviews the previous literature on the application of these methods in forestry and other industries. Chapter 3 includes the modification of an existing optimization model to determine the maximum profit that can be gained by each coalition, and the calculation of profit allocation using the methods reviewed in Chapter 2. Chapter 4 discusses the results of profit allocation in terms of the fairness-related properties and the relative savings at plants. In this chapter, different allocation methods are compared and evaluated, and a sensitivity analysis is performed to determine the sensitivity of allocation methods to the bio-product price, bio-product market demand, forest residue price, forest residue availability, sawmill residue price, and discount rate. Chapter 5 contains concluding remarks, limitations, and suggestions for future research.

Chapter 2: Literature review

2.1 Synopsis

In this chapter, first, an introduction to game theory concepts and notations that are fundamental to understand and evaluate different allocation methods is provided. Then, five categories of allocation methods based on game theory are reviewed. These methods include the Shapley value, the nucleolus, the methods based on separable and non-separable cost, the equal profit method, and the methods based on shadow or dual prices. Next, previous studies related to the application of game theory allocation methods in the forest industry and other industries are reviewed. It is indicated that the forestry sector has seen the frequent use of proportional methods, the nucleolus, and the equal profit method, mainly in collaborative logistics planning. On the other hand, other industries have studied a broader range of collaborative activities such as project development and service expansion. Finally, conclusions on the reviewed papers, and also suggestions about possible research opportunities are presented in this chapter.

2.2 Allocation methods

Many allocation methods have been proposed to address the problem of properly distributing the total costs or benefits among collaborative partners. The proportional method is probably the most straightforward one, which distributes the total cost according to each partner's shipping volume, stand alone cost, or other parameters. However, as pointed out in previous studies (e.g. Frisk et al. 2010), because the revealed data regarding such parameters may not be the actual information, the proportional methods often fail to generate a fair allocation to some partners, which will threaten the long-term success of the collaboration. Methods based on cooperative game theory, on the other hand, have been gaining popularity because they can provide many fairness-related properties. In order to introduce these methods, some basic game theory concepts and definitions are provided first (as shown in Table 2-1).

Table 2-1 Game theory notations

Symbol	Definition
j	Player *j*
N	The grand coalition
S	A sub-coalition
v(N)/v(S)	The characteristic function of *N/S*
$\boldsymbol{y_j}$	The allocated cost to player *j*

A partner in the collaboration is denoted as player j. The set of all players is denoted as the grand coalition *N*, and a subset of players is denoted as a sub-coalition *S*, $S \subset N$. When players in *N* or *S* collaborate, the value of *N* or *S* is denoted as *v(N)* or *v(S)*, which is the coalition's characteristic function. In the case of allocating on cost, the characteristic function is a cost function, written as *c(N)* or *c(S)*. The cost of the coalition is then distributed among players, where each player gets an allocated cost y_j. An allocation is said to be in the core if equations 2-1 and 2-2 are satisfied.

$$\sum_{j \in N} y_j = c(N) \tag{2-1}$$

$$\sum_{j \in S, S \subset N} y_j \leq c(S) \tag{2-2}$$

Equation (2-1) indicates that the total cost is distributed among all players, therefore the allocation is **efficient**. Equation (2-2) expresses that the players cannot obtain better costs in any sub-coalition compared to their allocated costs in the grand coalition, therefore the allocation satisfies **individual rationality**. The core is the set of all allocations that fulfill these two conditions, and any allocation in the core can be considered as a **stable** solution (Myerson, 2013).

In addition to efficiency, individual rationality and stability, an allocation can possess some of the following properties (Myerson, 2013; Shapley, 1988) :

1) Uniqueness, which ensures that there exists only one solution to the allocation problem.

2) Symmetry, which regulates that the players with the same contribution to the coalition should receive the same allocation.
3) Dummy player, which says that if a player does not benefit or harm any coalition, this player should receive nothing.
4) Anonymity, which indicates that the labelling of players does not affect the allocation.
5) Additivity, which means that if a coalition plays one cooperative game g1+g2 that can be decomposed into two different games g1 and g2, for each player, the allocation based on playing g1+g2 should be equal to the sum of the allocations based on playing g1 and g2 separately.

These properties provide a good basis for designing and comparing cost allocation methods, however, the difficulties arise as one method aims to possess too many properties. In fact, there is no method that can satisfy all these properties (Tijs & Driessen, 1986).

2.2.1 The Shapley value

The Shapley value is a widely used cost allocation method (Shapley, 1988). It satisfies properties related to efficiency, symmetry, dummy player, and additivity. Given a coalition, the Shapley value always exists and is unique, but it is not necessarily in the core, i.e., the allocation according to the Shapley value may not be stable.

The Shapley value allocates the average marginal cost to each player, supposing the players enter the grand coalition in completely random order. A mathematical expression of the Shapley value is as follows:

$$y_j = \sum_{\substack{S \subset N \\ j \in S}} \frac{(|S|-1)!(n-|S|)!}{n!} [c(S) - c(S - \{j\})] \tag{2-3}$$

In Equation (2-3), the factorial of S, $|S|$, is the number of players in S. The value of $\frac{(|S|-1)!(n-|S|)!}{n!}$ is therefore the number of all possible orders in which player j enters the grand coalition. The value of $c(S) - c(S - \{j\})$ is the amount of increase in coalition S's total cost due to player j's entry, i.e., player j's marginal cost.

2.2.2 The nucleolus

The nucleolus is another frequently used allocation method, which is introduced by Schmeidler (1969). Given an allocation $\vec{y} = (y_1, y_2, , , y_j)$ that assigns value y_j to player j in the grand coalition *N*, every sub-coalition *S* has a certain level of unhappiness towards this allocation, resulted from compromise or comparison with other coalitions. The measurement of unhappiness for sub-coalition *S* is defined as the excess $e(\vec{y}, S)$ and shown in Equation (2-4):

$$e(\vec{y}, S) = v(S) - \sum_{j \in S} y_j \tag{2-4}$$

The nucleolus method finds the allocation that minimizes the maximum unhappiness, taking all sub-coalitions into consideration. More precisely, the nucleolus lexicographically minimizes the vector of excesses when the excesses are arranged in non-increasing order. The nucleolus method has many desirable properties, including uniqueness, stability, symmetry, and the dummy player.

2.2.3 Methods based on separable and non-separable costs

This type of method divides the grand coalition *N*'s total cost into two parts: separable costs and non-separable costs. Player j's separable cost m_j is defined as the amount of increase in *N*'s total cost due to player *j*'s entry, i.e. the marginal cost as shown in Equation (2-5):

$$m_j = c(N) - c(N - \{j\}) \tag{2-5}$$

Each player is responsible for their own marginal cost. The total separable cost of *N* is therefore the sum of all players' separable cost, which can be written as $\sum_{j \in N} m_j$. After subtracting the total separable costs $\sum_{j \in N} m_j$ from *N*'s total cost, the remaining part is *N*'s non-separable cost $g(N)$, which is shown in Equation (2-6):

$$g(N) = c(N) - \sum_{j \in N} m_j \tag{2-6}$$

In Equation (2-6), $g(N)$ is then distributed according to each player's weight (w_j). The weight, w_j, can be determined based on different allocation methods:

1) Equally Charged Method (ECM): *g(N)* is equally shared, namely same w_j for each player. As simple as it is, the ECM ignores the differences in individual player's contribution to the coalition.
2) Alternative Cost Avoided Method (ACAM): *g(N)* is allocated based on each player's saving, which is the difference between the player's stand-alone cost $c(\{j\})$ and their separable cost m_j, namely $w_j = c(\{j\}) - m_j$. The ACAM satisfies efficiency and symmetry.
3) Cost Gap Method (CGM): *g(N)* is allocated based on the minimal cost each player needs to pay to form a coalition *S*, if all other players in this coalition only pay for their separable costs. This method is brought by Tijs and Driessen (1986). To understand it, assume in a coalition *S* all players pay for their separable costs. For player *j*, in addition to their separable cost, they also pay for the remaining cost *g(S)*:

$$g(S) = c(S) - \sum_{j \in S} m_j \tag{2-7}$$

In this case, player *j* wants to find a coalition S that has the lowest *g(S)* calculated by Equation (2-7), and this lowest *g(S)* is therefore the highest cost player *j* would like to be allocated in *N*, otherwise player *j* could leave *N* to form *S*. As a result, player *j*'s weight w_j is the minimum *g(S)* as in Equation (2-8):

$$w_j = min_{S:j \in S} g(S) \tag{2-8}$$

The CGM satisfies stability, symmetry, and the dummy player.

2.2.4 The equal profit method

The equal profit method (EPM) can be formulated as a linear programming problem which aims at minimizing the maximum difference in relative savings (denoted as *f*) among any pair of players in the collaboration. Assume there are two players: player *i* and player *j*. The relative saving of player i is expressed as $\frac{c(\{i\}-y_i}{c(\{i\})} = 1 - \frac{y_i}{c(\{i\})}$, and therefore the difference of pairwise relative saving between player j and player i is $(1 - \frac{y_j}{c(\{j\})}) - (1 - \frac{y_i}{c(\{i\})}) = \frac{y_i}{c(\{i\})} - \frac{y_j}{c(\{j\})}$.

The linear programming model of EPM can be written as follows:

Min f

$$s.t.\ f \geq \frac{y_i}{c(\{i\})} - \frac{y_j}{c(\{j\})}, \forall(i,j) \quad (2\text{-}9)$$

$$\sum_{j \in S, S \subset N} y_j \leq c(S) \quad (2\text{-}10)$$

$$\sum_{j \in N} y_j = c(N), -y_j \geq 0, \forall i \quad (2\text{-}11)$$

Equation (2-9) measures the difference in pairwise relative savings, and the largest difference represented by f is minimized in the objective function. Equation (2-10) and equation (2-11) express the constraints of individual rationality and efficiency, respectively.

2.2.5 Methods based on shadow or dual prices

The coalition's characteristic function can sometimes be formulated as a linear programming model with one objective function and many constraints. Each constraint has a shadow price, which is the marginal cost of each resource (constraint). The decision variables in the dual problem of the linear programming model indicate the shadow prices. As each player enters the coalition, they will bring in new resources and limitations, which changes the objective function and the constraints. Correspondingly, the change in the dual objective function value is defined to be the player's allocated cost or benefit.

2.3 Applications of allocation methods in forestry and other industries

This section provides a review of literature on the application of game theory allocation methods in two categories: studies that focused on the forestry sector and studies that focused on other industries.

2.3.1 Allocation in the forestry sector

The forestry sector has seen applications of game theory allocation methods, mostly in analyzing collaborative transportation activities.

Audy et al. (2007) studied the impact of the leaders' behavior in building a wood fiber flow collaboration and sharing the benefits. The leaders had the right to decide the timing and the sequence to take new players into the coalition. In this study, the leader was determined to be a customer that aimed to minimize its own transportation cost, while still provided enough incentives for the other players to stay in the coalition. When a new player was added, the incentives for non-leading players would increase if the leader had altruistic behavior, sharing the increase of benefits with all the players in the coalition. Otherwise, if the leader showed opportunistic behavior and took over all the amount of increase, the incentives for non-leading players would remain constant once they joined the coalition. These two types of behavior were simulated in a collaborative model of eight forest companies. The proportional method according to companies' stand-alone costs was adopted in the model to allocate the coalition's total costs or total benefits. The results showed that the coalition's building process varied under different leader's behavior when employing cost/saving allocation. The leader with opportunistic behavior under saving allocation approach could obtain the highest benefit. As the leader wanted to maximize their own payoff, the coalition could not catch all the attainable benefits.

In additional to the established allocation methods, new methods have been proposed in the forestry sector. Frisk et al. (2010) introduced the equal profit method (EPM). EPM is designed to minimize the maximum difference in pairwise relative savings, and to satisfy the efficiency and individual rationality properties. In other words, the allocation given by EPM is stable (in the core). In this study, EPM and other allocation methods including the Shapley value, the nucleolus, the proportional method based on the volume, allocation based on separable and non-separable costs, and allocation based on shadow prices were evaluated in a case study involving eight forest companies who had the coordination opportunities to implement wood bartering and backhauling. The results proved that EPM returned the most evenly distributed savings, while allocation based on separable and non-separable costs, shadow price, and volume generated unstable results where some companies would lose profit as they joined the coalition. The authors also studied the impact of backhauling, multiple time periods, and geographical distribution on the cost allocation. The results indicated that EPM and Shapley value gave similarly structured results, while EPM was claimed to be more understandable and acceptable for the players.

The EPM was employed in (Audy & D'Amours, 2008) to analyze the collaborative transportation of four Canadian furniture companies. Furniture companies usually outsource their transportation to third party logistics (3PL) providers who operate in two modes: truckload (TL) and less-than-truckload (LTL). Under the TL mode, the shipments are consolidated to fill the truck, whereas under the LTL mode, the shipments are sent as they are ready. When the aforementioned four companies collaborated, the TL and LTL modes could be combined. Therefore, the authors considered four possible collaborative scenarios, which included the pure LTL mode, the TL mode with terminal at one company, and two hybrid TL/LTL modes with terminal at two different locations operated by 3PLs. Under each scenario, the savings were allocated using three different methods: EPM, the proportional method according to the shipping volume, and the proportional method according to the shipping volume per delivery route. The case study demonstrated that it was possible for some players to lose profit or extend delivery time even though the scenario's total cost or delivery time was reduced. The implementation of collaboration was deeply affected by the leadership, which was usually taken by the company with the highest shipping volume. Such leaders could use their strong position in the coalition to pursue a sub-optimal scenario that did not provide the highest savings for the group, and negotiate a larger part of savings.

The EPM was further modified in (Audy et al., 2011). Compared to the original EPM, in this modified EPM, the authors introduced a minimum saving percentage which can be negotiated among players. They also added extra calculations to the original EPM to separate three non-transferable costs from each player's allocated cost. The non-transferable costs include costs incurred from volume flat rate charges at the terminal, from transportation upstream to the terminal, and from special requirements of each player. The cost of special requirements is calculated based on the modified Alternative Cost Avoided Method (ACAM) which assigns the highest costs to the most expensive requirements. These two modified methods were applied to a case study involving four Canadian furniture companies that wanted to plan their transportation collaboratively. It was proven that the minimum saving percentage was important to secure a non-zero saving for companies, and companies with tight delivery time or reluctance to some carriers would lose profits, which emphasized the value of flexibility in the transportation collaboration.

Another study regarding the leadership in the collaboration was conducted in (Audy et al., 2012). Instead of limiting the leader to one customer as in (Audy et al., 2007), in this study the authors explored 4 leadership scenarios: 1) leadership taken by the largest player; 2) leadership taken by the second largest player with a player completing its coverage; 3) leadership taken by the two mid-sized players; 4) leadership taken by the four smaller players. It was shown in the case study that regardless of the leadership scenarios, opportunistic behavior and saving allocation approach would always be more advantageous for the leaders. Being a leader could provide better return for each player, especially for the largest company, whose payoff could be up to 80.4% higher as the sole leader. For smaller companies, when they shared the leadership, the selection of partners would also impact the payoff. Additionally, without changing the formation of the coalition, just by deciding the optimal sequence to take in the new players, the leaders could obtain 1.1-10.6% additional payoff.

Flisberg et al. (2015) also modified the EPM method. In their adapted EPM (denoted as AEPM), the constraint of individual rationality is relaxed to simplify the computational process. If there are n players in the game, the EPM requires calculating the cost for $2^n - 1$ sub-coalitions to guarantee the individual rationality, whereas the AEPM only needs calculating the cost for $2n + 1$ sub-coalitions. Clearly, the AEPM is more practical for large scale cooperative games. The country-wide case study presented in this paper was such a game, involving 61 companies with more than 6.1 million tons of biomass. The aim of the study was to assess the value of several improvement opportunities in biomass logistics, including proper scheduling of transportation, using the mix of different biomass at bio-energy plants, and collaboration. The optimal transportation plan was solved by a linear programming model, with the objective function of minimizing the total cost. The savings from the collaboration were then distributed using the modified nucleolus, the proportional methods according to volumes and stand-alone costs, allocation based on separable and non-separable costs, and AEPM. The results stated that if all improvement opportunities were realized, the total savings could be as high as 22%, equivalent to 19 million USD. Among all allocation methods, the proportional methods often failed to insure stable collaboration. The modified nucleolus and the methods based on separable and non-separable, despite their success in securing stability, would lead to significant difference in relative savings ranging from 0.5% to 31.2%. On the other hand, the difference in the relative savings resulted from the AEPM only varied between 1.1% and 8.6%.

Table 2-2 Summary of literature on cost allocation in the forestry sector

Author (Year)	Region/Area	Type of supply chain activities	Allocation methods	Key aspects
Audy et al. (2007)	Canada/Forestry	Transportation	• The proportional method	• The leader's behavior impacted the coalition's building process. • The leader with opportunistic behavior under the saving allocation approach could obtain the highest benefit. • The coalition could not obtain all the attainable benefits because the leader aimed at maximizing its own profits.
Audy et al. (2008)	Canada/Furniture	Transportation	• The proportional method • The equal profit method	• When the coalition's total cost or total delivery time was reduced, it was possible that some players would lose profit or had increased delivery time. • The selection of the collaboration plan and cost allocation methods depended on which company was in the leading position.
Frisk et al. (2010)	Canada/Furniture	Transportation	• The Shapley value • The nucleolus • The proportional method • Allocation based on separable and non-separable costs • The allocation method based on shadow price • The equal profit method	• The equal profit method was developed and compared with other cost allocation methods. • The equal profit method could fairly distribute savings, and was claimed to be more understandable and acceptable by the players.

Table 2-3 Cont. Summary of literature on cost allocation in the forestry sector

Author (Year)	Region/Area	Type of supply chain activities	Allocation methods	Key aspects
Audy et al. (2011)	Canada/Furniture	Transportation	• The modified equal profit method • The modified Alternative Cost Avoided method	• The equal profit method was modified to include a minimum saving percentage and to separate three non-transferable costs from each player's allocated cost. • The minimum saving percentage was important to secure a non-zero saving for companies. • Companies with tight delivery time or reluctance to some carriers would lose profit.
Audy et al. (2012)	Canada/Forestry	Transportation	• The proportional method	• Different types of leadership were assessed. • Under each leadership, opportunistic behavior and the saving allocation approach would always be more advantageous for the leaders. • The leader was able to earn a total 1.1-10.6% additional payoff just by deciding the optimal sequence to add new players.
Flisberg et al. (2015)	Sweden/Bio-energy	Transportation	• The nucleolus • The proportional method • The allocation method based on separable and non-separable costs • The adapted equal profit method	• The equal profit method was simplified to adapt the large scaled case study. • The adapted equal profit method generated 1.1% - 8.6% in relative savings, while the difference resulted from other allocation methods led to 0.5% - 31.2%.

2.3.2 Allocation in other sectors

There are many studies in other industries that incorporate cooperative game theory concepts to solve cost allocation problems. For example, the logistics industry is a very active field. In addition to logistics, Fiestras-Janeiro et al, (2011) listed many cost allocation studies performed in two other areas: natural resources and power industry. Problems in the natural resources included the construction of multi-purpose facilities such as water supply system and waste-water treatment system, transportation of natural resources, and environmental management such as pollution reduction. Problems in the power industry focused on the restructuring process of the power supply network, changing from monopolies to a more competitive environment.

A famous study incorporating game theory concepts in natural resource management is done by Straffin & Heaney (1981). In this paper, the authors introduced a cost allocation method for the planning of water resource development projects in the Tennessee Valley, US. The purposes of those projects included navigation improvement, flood control, and power generation, which would impact the electricity price in this area. These purposes were considered as the players in the game to allocate the total budget. The proposed allocation method, called the Alternative Cost Avoided Method (ACAM), was developed based on the concepts of game theory including the Shapley value and the nucleolus. ACAM first assigns each player a "separable cost", which is the amount of increase in a project's total cost due to including this player (purpose) into the project design. After subtracting all the separable costs, the remaining part is a project's non-separable cost, which is allocated based on the savings made by having one player (purpose) in the multi-purpose project instead of designing a single-purpose project for this player. The ACAM was then modified to include the constraint that a single-purpose project was only possible when it could earn profits. The modified ACAM got the widest acceptance from water resource engineers in the Tennessee Valley, and is still in use today.

Engevall et al. (2004) reviewed the requirement of a nonempty core in the vehicle-routing cooperative game to simplify the computation of the nucleolus method. The vehicle-routing game presented in this paper aimed at minimizing the total transportation cost through the selection of routes, customers and vehicles, and the transportation cost was paid by the customers who were served. The set of customers was considered to be feasible if their demand could be satisfied using only one truck. This vehicle-routing problem could be formulated into a cooperative game, where the customers formed a collaboration to share the transportation cost. If there were *n* customers in the collaboration, the transportation cost for visiting all the customers was denoted as c(N). The authors stated that if c(N) is equal to the optimal objective function value from the vehicle routing game, the core of the game was not empty. In this case, the computation of the nucleolus method could be simplified by only considering the feasible sets of customers. The nucleolus, together with the Shapley value and the proportional method based on the volume and based on the volume per route, were adopted in a case study at the logistics department of a gas-oil company. It was observed that the Shapley value allocated higher costs than the nucleolus method to small customers. The proportional method based on the volume allocated very high costs to closest customers because it did not consider the geographical locations of customers. However, the proportional method based on the volume per route, where each customer's cost per volume was calculated for each route first and then added up, was a good approximation of the nucleolus method, and was employed by the company.

An example of the cost allocation in the power industry is by Erli et al. (2005). The authors studied the allocation of the power transmission expansion cost among the participants in the electric market. The expansion aimed at relieving the congestion in the power system, and the participants were one electric utility, two independent power producers, and eligible customers, all benefiting from the expanded lines. In order to share the benefits, they formulated the nucleolus into a linear programming model, with the objective function of maximizing the minimum happiness of the participants. The nucleolus succeeded in providing an equitable allocation, based on which each participant could evaluate the profitability of the collaboration.

Agarwal & Ergun (2010) introduced a new mechanism for collaboration on ship transportation. This mechanism was designed to establish an efficient network, simulate the interaction among players, and share the costs/benefits of the coalition. The mechanism include three models. The first model maximizes the coalition's profit by optimizing the service routes and the delivery of cargos. Once the set of service routes is selected, the assignment of ships is determined in the second model, and the cost allocation, in the form of side payments, is accomplished in the third model. The allocated cost is calculated based on the fraction of shipping capacity owned by each player on each service route. The performance of the mechanism was evaluated in a computational study. The result illustrated that in almost all scenarios, as long as the core is nonempty for the collaboration, i.e. there existed stable allocation, this mechanism could successfully find the core. The increase in the number of players would make it more difficult to find the core, however, the percentage improvement in the coalition's revenue also increased as the coalition expanded.

Ramaekers, Verdonck, Caris, Meers, & Macharis (2017) assessed the collaboration among on barge transportation. The players collaborated by bundling freights and sharing vessel capacity, and the incurred costs could be distributed using the proportional method based on the shipping volume (denoted as the proportional method), the proportional method based on the shipping volume and distance per common transport routes (denoted as the decomposition method), the Shapley value, and the equal profit method (EPM). The application of these methods was evaluated in two case studies in the Netherlands. The first case study used a model with real data to forecast transport demand and generate logistic decisions for the collaboration. In this case study, if players were equal in shipment size, all allocation methods generated similar results. If players were unequal in shipment size, the Shapley value tended to favor players with smaller sizes, while the decomposition method benefited players that took part in more bundled freight. The size of the players and the size of the coalition had impact on the stability of the coalition. Since the first case study contained some assumptions that could not accommodate the economies of scale in warehousing or ordering, and required the demand and lead-time to follow a normal distribution, the second case was conducted with relaxed assumptions. In the second case study, small players could obtain the highest savings. In additional to the economic benefits, freight bundling could also provide better customer service.

Padilla Tinoco et al. (2017) studied the collaboration between two shipping companies. The two companies could choose from four types of cost-sharing agreements, under which they either paid for their own cost (no sharing at all), shared the cost of vehicles (denoted as major transportation cost), shared the cost of vehicles and the cost of handling (denoted as minor transportation cost), or shared the total logistics costs. The employed cost sharing methods were based on the three proportional methods and one game theory method. The proportional methods distribute the costs according to stand-alone costs, squared order frequencies, and squared stand-alone costs. The game theory method divides the gain of the collaboration in two equal parts. The authors conducted a numerical example to investigate the impact of cost-sharing agreements and allocation methods on the stability of the collaboration. The results indicated that when companies only paid for their own cost, the collaboration was always stable regardless of the allocation methods, therefore "no cost sharing" was the easiest agreement to implement. When other cost-sharing agreements were employed, the dependence between stability and allocation methods increased as more costs were shared, and in this case the game theory method had obvious advantages. It was worth noting that all the computations in this study only involved two companies, which might not be a fair representation of a bigger collaboration.

Table 2-4 Summary of literature on cost allocation in other sectors

Author (Year)	Region/Area	Type of supply chain activities	Allocation methods	Key aspects
Straffin and Heaney (1981)	US/Water Resource	Resource management	• The Alternative Cost Avoided Method	• The Alternative Cost Avoided Method and a modified version were developed to evaluate the water resource development projects in the Tennessee Valley, US. • Compared with other allocation methods, the authors claimed that this method got the widest acceptance from local water resource engineers.
Engevall et al. (2004)	Sweden/Logistics	Transportation	• The proportional method • The Shapley value • The nucleolus	• The computation of the nucleolus could be simplified if the core of the collaboration game was not empty. • The proportional method according to the volume per route was proved to be a good approximation of the nucleolus, in which each customer's cost per volume was calculated for each route first and then was added up.
Erli et al. (2005)	Japan/Power	Supply chain expansion	• The nucleolus	• The nucleolus succeeded in providing an equitable cost allocation for power transmission expansion.

Table 2-5 Cont. Summary of literature on cost allocation in other sectors

Author (Year)	Region/Area	Type of supply chain activities	Allocation methods	Key aspects
Agarwal and Ergun (2010)	US/Logistics	Transportation	• The proportional method	• The cost was allocated in forms of side payments, based on the fraction of shipping capacity owned by each player on each service route. • The increase in the number of players would make it more difficult to find a stable allocation, while the percentage improvement in the coalition's revenue also increased as the coalition expanded.
Ramaekers et al. (2017)	Belgium/Logistics	Transportation	• The proportional method • The Shapley value • The equal profit method	• The size of the players and the size of the coalition had impact on the stability of the coalition. • Allocation methods adopted in this study showed different preferences towards players if they were unequally sized. • In additional to economic benefits, freight bundling could also provide better customer service.
Padilla Tinoco et al. (2017)	Belgium/Logistics	Transportation	• The proportional method • The game theoretical method dividing the gain of the collaboration in two equal parts	• For a collaboration of two players, "no cost sharing at all" could be the easiest way to share the total costs so that each player paid for its own costs incurred from logistics activities, and in this way the collaboration was always stable. • The dependency between stability and allocation methods increased as more costs were shared, where game theory methods had obvious advantages. • All the computations in this study only involved two companies, which might not be a fair representation of a bigger collaboration.

2.3.3 Discussion

Previous literature in the forestry sector mainly addressed two kinds of problems in collaborative logistics planning: a) the impact of leadership on coalition and cost sharing, and b) the stability and fairness of the cost allocation methods.

The collaborative transportation in forestry could be driven by one or more leaders, being the customers or the logistics providers (Audy et al., 2007), while in most cases the leadership was taken by the company with the highest shipping volume (Audy & D'Amours 2008). The leadership empowered companies to decide the timing and the sequence to take new players into the coalition. With this privilege and the aim of maximizing their own profits, the leaders tended to behave opportunistically to realize a sub-optimal allocation that could not catch all the attainable benefits, and to negotiate a larger part of savings (Audy & D'Amours 2008; Audy et al., 2012). On the other hand, although being a leader, especially being the sole leader, could generate additional profits for companies, it also required heavy investments on human resources, time, and capital. As a result, it was necessary for some companies to share the leadership with one or more players (Audy et al., 2012).

In the forestry sector, the commonly reviewed cost allocation methods included the proportional method, the nucleolus, and the equal profit method. The proportional method was easy to implement, while it was proved to be non-stable in many situations (e.g. Flisberg et al., 2015). The nucleolus method always gave a stable allocation as long as there existed such allocation; however, the computation of the nucleolus was so complicated for large-scaled coalitions that reasonable simplifications had to be adopted for its application in case studies. That being said, in practice the number of companies collaborating on transportation was usually limited to two (Frisk et al., 2010), therefore the utilization of the nucleolus was made possible. The equal profit method was developed to guarantee the fairness in cost allocation, and it was modified to include different constraints such as a minimum saving and a relaxed individual rationality. The equal profit method and its modifications had advantages in equalizing relative savings among players. However, the non-uniqueness of the equal profit method was pointed out in (Dahlberg et al., 2017). When the solution is not unique, the allocated cost of at least two players are allowed to change under the same objective function value, and one player may be allocated a higher cost as a result of this arbitrariness. To prevent this, additional modifications based on lexicography can be added to the equal profit method.

The similarities between the literature in the forestry sector and other sectors include the frequent application of the proportional method, and noting to its limitation on securing stability in many studies (e.g. Padilla Tinoco et al., 2017). However, in contrast to research in forestry which mostly focused on logistics activities, literature in other sectors extended the scope of cost allocation study to project development (in the water resource management) and service expansion (in the power industry). The field of water resource management had seen the development of the Alternative Cost Avoided Method. This method was used in many follow-up research studies on similar topics (e.g., Teasley and McKinney 2011, Madani and Dinar 2012), and one formula developed in this method has become the standard for cost allocation in multi-purpose reservoir planning (Young, 1994). The area of power industry adopted the nucleolus and the Shapley value as the most used cost allocation methods (Fiestras-Janeiro et al., 2011). The nucleolus method was adapted in different ways so that the computation could be simplified (e.g. Erli et al., 2005), and the Shapley value was observed to show preference towards smaller players (Engevall et al., 2004; Ramaekers et al. 2017).

2.4 Conclusions

A number of game theory cost allocation methods and their applications in forestry and other industries were reviewed in this chapter. It was revealed that in the forestry sector, cost allocation studies were mostly related to collaborative transportation, whereas in other industries such studies were also concerned with different supply chain activities such as project planning and network expansion. Therefore, extending the scope of collaboration in forestry can be a possible topic for future research.

Regardless of industries, cost allocation problems could be solved with an optimization model to first maximize the profits for all supply chain partners, and then the profits were distributed based on the aforementioned game theory methods, which can satisfy different properties. It is important to remember that there is no single best solution to such kind of problems, and the selection of the cost allocation method should consider both the specific goal of the collaboration and the incentives for individual supply chain partners. Moreover, it is common to modify the established cost allocation methods to increase their suitability for practical cases.

Another research topic that can be investigated in the future is the intangible benefits of collaborations, including but not limited to the growth in geographic coverage, the access to different markets, and the improvement in service levels. Although it is difficult to share them in monetary terms, the value of these benefits can be reflected in the cost allocation model, for example, by assigning a larger part of savings to participants who have the biggest contribution in completing the geographical coverage of the collaboration.

Last but not least, it should be noted that partners in the collaboration are usually different in size. The larger ones who have stronger position are likely to demand more benefits to be allocated to themselves, while smaller partners will probably compromise as long as they can still benefit from the collaboration. The strategies and behaviors of the supply chain partners and their negotiation process are frequently analyzed in the approach of non-cooperative game theory, an extensive review of which is provided in (Cachon and Netessine 2006), and the application of this approach in forestry is an interesting research opportunity.

Chapter 3: Optimization of the forest biomass supply chain and profit allocation

3.1 Synopsis

A number of allocation methods were introduced in Chapter 2, and it was revealed that the previous research regarding cost/profit allocation in forestry did not involve supply chain activities other than transportation. In this chapter, the collaboration among three bio-energy and bio-fuel conversion plants in terms of sawmill residue exchange is closely examined.

This chapter can be divided into two parts. First, an optimization model developed in (Akhtari et al., 2018) is modified to determine the optimal biomass flow and the type of conversion technology at each conversion plant, with the goal of maximizing the net present value of the total profit that can be obtained by all the three plants. Then, additional modifications are added to the optimization model in order to optimize the supply chain of only one or two plants, while the selected technology types would remain the same. The results from the optimization model provide a foundation for profit allocation, to which the allocation methods are applied.

The second part presents the profit allocation results according to the following methods: the Shapley value, the nucleolus, two proportional methods that are based on stand-alone profits and volume of biomass used at each conversion plant, three methods based on separable and non-separable cost (ECM, ACAM, CGM), and the equal profit method. These methods are evaluated based on efficiency and individual rationality properties, and recommendations are made to facilitate the selection of allocation methods for this specific collaboration.

3.2 Problem formulation

The optimization model in this study is developed based on the model designed by (Akhtari et al., 2018), therefore a similar design and structure of the supply chain is adopted. The supply chain begins with two possible sources of forest-based biomass, which are harvesting residues collected at forest roadsides and sawmill residues obtained from sawmills. Then, the residues are sent to conversion facilities that are assumed to be at the sawmill locations. Different types of conversion technology are prescribed for each conversion plant by the model, and the corresponding bio-energy and bio-fuel are produced and then used or sold to markets. Figure 3.1 provides a general schematic of the supply chain.

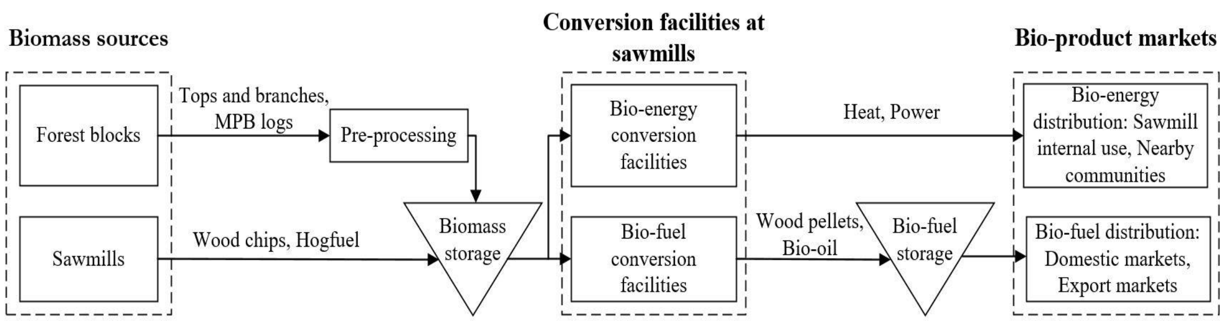

Figure 3-1 Forest-based biomass supply chain

Specifically, the harvesting residues used in this supply chain include tree tops, branches, and mountain pine beetle (MPB) killed logs. Before transported to conversion facilities, harvesting residues are first gathered in piles and chipped at roadside of the forest cut blocks. Therefore, utilizing harvesting residues is associated with preprocessing, which requires additional equipment and labor. On the other hand, sawmill residues, which include clean wood chips and hog fuel in this study, can be directly sent to conversion facilities without further processing.

The forest-based biomass is then converted into bio-products. The availability of biomass and the desirability of bio-products together determine the selection of conversion technologies. The bio-products are mainly bio-fuel and bio-energy. Bio-fuel including wood pellets and bio-oil can be sold locally or be exported to other markets. Bio-energy, namely heat and power, is primarily used to meet the internal demand in the plants, and then distributed to nearby communities.

The optimal design of the supply chain can be formulated as a linear programming (LP) model. The model covers 20 years of planning in monthly time steps with the objective to maximize the net present value of the investment. It assists decisions on 1) the sources and types of forest-based biomass, 2) the quantity of biomass to be collected, transported, stored, and converted, 3) the locations, technology types, and capacities of the conversion plants, 4) the amount of bio-products to be produced, stored, and sold. A simplified description of the model is given below for illustration purposes. Table 3-1, Table 3-2, and Table 3-3 present the sets, parameters, and decision variables of the optimization model. The objective function and constraints are explained below in details.

Table 3-1 List of sets of the model

Sets	
$\boldsymbol{B} = \{\mathbf{1}, \mathbf{2}, \dots, \boldsymbol{b}\}$	Set of biomass types
$\boldsymbol{I} = \{\mathbf{1}, \mathbf{2}, \dots, \boldsymbol{i}\}$	Set of biomass supply points
$\boldsymbol{K} = \{\mathbf{1}, \mathbf{2}, \dots, \boldsymbol{k}\}$	Set of candidate conversion technologies
$\boldsymbol{L} = \{\mathbf{1}, \mathbf{2}, \dots, \boldsymbol{l}\}$	Set of locations for conversion plants, assumed to be at the sawmills
$\boldsymbol{M} = \{\mathbf{1}, \mathbf{2}, \dots, \boldsymbol{m}\}$	Set of markets
$\boldsymbol{P} = \{\mathbf{1}, \mathbf{2}, \dots, \boldsymbol{p}\}$	Set of bio-energy and bio-fuel products
$\boldsymbol{P_e} \subset \boldsymbol{P}$	Set of bio-energy products
$\boldsymbol{P_f} \subset \boldsymbol{P}$	Set of bio-fuel products
$\boldsymbol{S} = \{\mathbf{1}, \mathbf{2}, \dots, \boldsymbol{s}\}$	Set of annual time periods
$\boldsymbol{T} = \{\mathbf{1}, \mathbf{2}, \dots, \boldsymbol{t}\}$	Set of monthly time periods

Table 3-2 List of parameters of the model

Parameters	
$BA_{b,i}^{t,s}$	Biomass availability of type *b* at supply point *i* in month *t* of year *s*
BC_b	Biomass purchase cost per odt for biomass type *b*
$CD_{b,e,k}$	Conversion facility energy demand to convert one odt biomass type *b* into bio-energy *e* by technology *k*
CL	Biomass loss due to chipping
$EC_{p,l}$	Energy cost when fossil-based energy, instead of bio-product *p*, are used to meet one unit of energy demand at location *l*
FC_k	Annual fixed cost of conversion technology *k*
IC_k	Investment cost of conversion technology *k*
IR	Discount rate
$MD_{p,m}^{t,s}$	Market demand of bio-product *p* at market *m* in month *t* of year *s*
PC_b	Biomass preprocessing cost per odt for biomass type *b*
$PR_{p,m}$	Unit selling price of bio-product *p* in market *m*
$SC_{b,l}$	Biomass monthly storage cost per odt for biomass type *b* at location *l*
$SC_{f,l}$	Bio-fuel monthly storage cost per unit for bio-fuel type *f* at location *l*
$SD_{e,l}^{t,s}$	Sawmill energy demand of energy type *e* at location *l* in month *t* of year *s*
$TC_{b,i,l}$	Biomass transportation cost for biomass type *b* from supply point *i* to location *l*
$TC_{p,l,m}$	Bio-product transportation cost for bio-product type *p* from location *l* to market *m*
TS_k	Maximum capacity of technology *k* (measured in terms of biomass input)
UF_k	Minimal utilization factor of technology *k*
$VC_{b,k}$	Variable cost of converting one odt biomass type *b* by technology *k*
$YL_{b,e,k}$	Yield of converting biomass type *b* to bio-energy product type *e* by technology *k*

Table 3-3 List of decision variables of the model

Decision variables	
$\boldsymbol{o_{b,i,l}^{t,s}}$	Amount of biomass type *b* from supply point *i* to plant location *l* in month *t* of year *s*
$\boldsymbol{q_{k,l}^{s}}$	Binary variable: 1, if technology *k* is installed at location *l* in annual time period *s*; 0, otherwise
$\boldsymbol{u_{b,k,l}^{t,s}}$	Amount of biomass type *b* converted by technology *k* at location *l* in month *t* of year *s*
$\boldsymbol{v_{e,l}^{t,s}}$	Amount of bio-energy product *e* used to meet conversion facility energy demand at location *l* in month *t* of year *s*
$\boldsymbol{w_{e,l}^{t,s}}$	Amount of bio-energy product *e* used to meet sawmill energy demand at location *l* in month t of year *s*
$\boldsymbol{x_{p,l,m}^{t,s}}$	Amount of bio-energy and bio-fuel product *p* sold from location *l* in to market *m* in month *t* of year *s*
$\boldsymbol{y_{f,l}^{t,s}}$	Amount of bio-fuel product *f* stored at location *l* in month *t* of year *s*
$\boldsymbol{z_{b,l}^{t,s}}$	Amount of biomass type *b* stored at location *l* in month *t* of year *s*

The objective function is presented in Equation (3-1):

$$\text{Max NPV} = \sum_s \left(\frac{(TotalRevenue_s - TotalCost_s)}{(1+IR)^s} - \frac{\sum_k \sum_l IC_k (q_{k,l}^{s} - q_{k,l}^{s-1})}{(1+IR)^{s-1}}\right) \tag{3-1}$$

Equation (3-1) maximizes the net present value (NPV) of the total profit that can be obtained by the supply chain over the planning horizon. The first term is sum of the annual profit (annual revenue minus annual cost) over all years, s. The second term is the annual investment cost of technology k at location l over all years, s. It is assumed that the technology k has to be installed at the beginning of a time period (year), not necessarily the first time period (year). In other words, it is possible for the optimization model to select a technology k at location l in any years during the planning horizon.

The total revenue in time period *s* is determined in Equation (3-2) by adding up the sales of bio-energy and bio-fuel products, the savings from replacing fossil-based energy which is currently used to meet the energy demand, and the sales of surplus sawmill residues from one conversion plant to another conversion plant.

$$TotalRevenue_s = \sum_p \sum_l \sum_m \sum_t PR_{p,m} \times x_{p,l,m}^{t,s} + \sum_{e \in P_e} \sum_l \sum_t EC_{e,l} \times SD_{e,l}^{t,s} + \sum_b \sum_{i=l' \neq l} \sum_l \sum_t BC_b \times o_{b,i,l}^{t,s} \quad (3\text{-}2)$$

The total cost in time period *s* includes biomass purchase, preprocessing, transportation and storage costs, as well as fixed production, variable production, bio-fuel storage and bio-product transportation costs, as shown in Equation (3-3) to Equation (3-10). Besides, if the amount of the produced bio-energy is not enough to cover the entire energy demand by the sawmill and the conversion facility at location *l*, fossil-based energy will be purchased, the cost of which is calculated by Equation (3-11).

$$BiomassPurchaseCost_s = \sum_b \sum_i \sum_l \sum_t BC_b \times o_{b,i,l}^{t,s} \quad (3\text{-}3)$$

$$BiomassPreprocessingCost_s = \sum_b \sum_i \sum_l \sum_t PC_b \times o_{b,i,l}^{t,s} \quad (3\text{-}4)$$

$$BiomassTransportationCost_s = \sum_b \sum_i \sum_l \sum_t TC_{b,i,l} \times o_{b,i,l}^{t,s} \quad (3\text{-}5)$$

$$BiomassStorageCost_s = \sum_b \sum_l \sum_t SC_{b,l} \times z_{b,l}^{t,s} \quad (3\text{-}6)$$

$$FixedProductionCost_s = \sum_k \sum_l FC_k \times q_{k,l}^{s} \quad (3\text{-}7)$$

$$VariableProductionCost_s = \sum_b \sum_k \sum_l \sum_t VC_{b,k} \times u_{b,k,l}^{t,s} \quad (3\text{-}8)$$

$$BiofuelStorageCost_s = \sum_{f \in P_f} \sum_l \sum_t SC_{f,l} \times y_{f,l}^{t,s} \quad (3\text{-}9)$$

$$BioproductTransportationCost_s = \sum_p \sum_l \sum_m \sum_t TC_{p,l,m} \times x_{p,l,m}^{t,s} \quad (3\text{-}10)$$

$$FossilbasedEnergyCost_s = \sum_{e \in P_f} \sum_l \sum_t EC_{e,l} \times \left(\sum_b \sum_k (CD_{b,e,k} \times u_{b,k,l}^{t,s}) - v_{e,l}^{t,s} + SD_{e,l}^{t,s} - \sum_l w_{e,l}^{t,s}\right) \quad (3\text{-}11)$$

One may notice that the sawmill energy demand $SD_{e,l}^{t,s}$ appears in the calculation of both the total revenue (Equation (3-2)) and the total cost (Equation (3-11)). This reflects the consideration that when there is no conversion facility installed at one sawmill, i.e., the sawmill maintains status quo, its profit regarding bio-product conversion should be zero. Together, annual revenues and costs calculated by Equation (3-2) to Equation (3-11) make up for the future cash flows of coalitions, which are then converted into present values. For illustration purpose, an example of NPV calculation is given in Appendix A.

The optimization model is subject to a number of constraints, and the main ones are listed here (Equation (3-12) to Equation (3-16)):

$$\frac{1}{1-CL} \times \sum_l o_{b,i,l}^{t,s} \leq BA_{b,i}^{t,s} \tag{3-12}$$

Equation (3-12) restricts that in each time period, the amount of each biomass type purchased from each supply point should not exceed the maximum availability of this type of biomass in this time period.

$$\sum_l x_{p,l,m}^{t,s} \leq MD_{p,m}^{t,s} \tag{3-13}$$

Equation (3-13) ensures that in each time period, the amount of each bio-energy product generated in all locations should not be more than its market demand.

$$\sum_b \sum_k YL_{b,e,k} \times u_{b,k,l}^{t,s} = v_{e,l}^{t,s} + w_{e,l}^{t,s} + \sum_m x_{e,l,m}^{t,s} \tag{3-14}$$

Equation (3-14) states that the bio-energy products generated at each location are either used to meet the energy demand of the sawmill and the conversion facility, or sold to external markets.

$$UF_k \times TS_k \times q_{k,l}^s \leq \sum_b u_{b,k,l}^{t,s} \leq TS_K \times q_{k,l}^s \tag{3-15}$$

Equation (3-15) sets the lower and upper limits for the utilization rate of the conversion facility installed at each location.

$$q_{k,l}^s \geq q_{k,l}^{s-1} \tag{3-16}$$

Equation (3-16) ensures the continuous operation of the conversion facility. Once the technology is installed at one location, it should be in operation till the end of the planning horizon. In addition to the above constraints, all decision variables are non-negative variables.

3.3 Profit allocation results

The model first provided the optimum solution for the supply chain when all three plants were in coalition, which was called C7 here. According to this solution, the selected conversion technology type *k* at each location *l* was also determined by the model, as shown in Table 3-4.

Table 3-4 Optimum solution of the supply chain when three conversion plants collaborate

Plants	Biomass sources	Prescribed conversion technology	Bio-products
A	Harvesting residues MPB logs Hogfuel Clean wood chips	• 2 MW biomass boiler (CHP) • 45,000 tonnes/year pellet mill	Heat, electricity, pellets
B		• 0.5 MW biomass gasifier (Power only)	Electricity
C		• 1 MW biomass boiler (CHP) • 600 odt/day pyrolysis plant	Heat, electricity, bio-oil
Optimized NPV of C7			**$60,726,372**

The optimization model suggested installing a combined heat and power (CHP) boiler and one pellet mill at plant A. The produced heat and electricity would be mainly for internal use, and the pellets would be sent to export markets. Plant B should have a small-scaled biomass gasifier, producing electricity only. Plant C should be equipped with a biomass CHP boiler, and a pyrolysis plant. Similarly, the heat and electricity would be largely used to meet the plant’s energy demand, while the bio-oil would be sold to distribution centers in local markets. The model concluded that the optimized NPV of C7 was about $61 million. However, in order to find the optimized NPV for coalitions C1 to C6, the optimization model had to be modified.

In the modified model, two subsets $\boldsymbol{C}$ and $\boldsymbol{N}$ are added to distinguish the collaborative plants (Eq. (3-17)) and non-collaborative plants (Eq. (3-18)).

$$C \subseteq L,\ set\ of\ collaborative\ plants \tag{3-17}$$

$$N \subseteq L,\ set\ of\ non-collaborative\ plants \tag{3-18}$$

For all non-collaborative plants in the subset N, since they are not collaborating and not included in the optimization model, their sawmill energy demand $SD_{e,l}^{t,s}$ and sawmill residue availability $BA_{b,i}^{t,s}$ are set to be zero (Eq. (3-19) and Eq. (3-20)) so that the collaborative plants in the subset C will not exchange sawmill residue with them or fulfill their energy demand. One may notice that the notation of $BA_{b,i}^{t,s}$ uses i instead of l. This is because in the model the set I contains not only forest cut blocks but also plants (Figure 3-1), as the plants can also be viewed as the supply points of sawmill residues from the perspective of collaboration.

$$SD_{e,l}^{t,s} = 0\ \ \forall l \in N \tag{3-19}$$

$$BA_{b,i}^{t,s} = 0\ \ \forall i \in N \tag{3-20}$$

In the original optimization model, a binary decision variable $q_{k,l}^{s}$ is used to determine what technologies should be installed at plants. However, in the modified model, in order to have comparable results, the collaborative plants should have the same technology type and size (as prescribed in the original model) in all coalitions, while the non-collaborative plants should not install any conversion technologies as they are excluded from optimization. Therefore, $q_{k,l}^{s}$ is not a decision variable anymore. Instead, the value of $q_{k,l}^{s}$ is determined by Eq. (3-21) and Eq. (3-22).

$$\forall \boldsymbol{l} \in \boldsymbol{C}, \boldsymbol{s} \in \boldsymbol{S}: \tag{3-21}$$

$q_{k,l}^{s}$=1, if

$$\begin{cases} l = plant\ A, k = 2\ MW\ CHP\ biomass\ boiler\ or\ 45000\ tonnes/year\ \ pellet\ mill; \\ l = plant\ B, k = 0.5\ MW\ power - only\ biomass\ gasifier; \\ l = plant\ C, k = 1\ MW\ CHP\ biomass\ boiler\ or\ 600\ \ odt/day\ pyrolysis\ plant; \end{cases}$$

$q_{k,l}^{s}$=0, Otherwise

$\forall \boldsymbol{l} \in \boldsymbol{N}, \boldsymbol{s} \in \boldsymbol{S}, \boldsymbol{k} \in \boldsymbol{K}$: (3-22)

$q_{k,l}^{s}$=0

The modified was then run multiple times for coalitions C1-C6. Table 3-5 shows the optimized results for each coalition, denoted as NPV_{C1} to NPV_{C7}.

Table 3-5 Optimized NPV of profit for each coalition

Optimized NPV of profit for coalitions	Value (in thousand Canadian dollars)
$\boldsymbol{NPV_{C1}}$ (plant A)	20,461
$\boldsymbol{NPV_{C2}}$ (plant B)	213
$\boldsymbol{NPV_{C3}}$ (plant C)	37,253
$\boldsymbol{NPV_{C4}}$ (plants A & B)	20,684
$\boldsymbol{NPV_{C5}}$ (plants A & C)	57,856
$\boldsymbol{NPV_{C6}}$ (plants B & C)	40,176
$\boldsymbol{NPV_{C7}}$ (plants A & B & C)	60,726

It is observed that C7 has the highest NPV of profit among all the coalitions. It indicates that the collaboration among plants A, B and C is the most profitable one, and the three plants should have the incentive to form C7 given that a fair plan is developed to share the total profit. Therefore, to distribute NPV_{C7} among player, allocation methods introduced in Chapter 2 are used. The profit allocation according to those methods are calculated and the results are described in Table 3-6 and Figure 3-2.

In Table 3-6, the column "Stand-alone NPV" represents the profits earned by plants A, B, and C when there is no collaboration and the plants all work individually, the values of which are equal to NPV_{C1}, NPV_{C2}, and NPV_{C3}. It is noticed that the sum of NPV_{C1}, NPV_{C2}, and NPV_{C3} is about 58 million, less than NPV_{C7} which is around 61 million. It once again proves that the three-plant collaboration is more beneficial than plants operating alone without exchanging sawmill residues. The remaining columns contain the profits distributed to each plant by the listed allocation methods and concepts. Some allocation methods give similar results while the others vary, and the difference is visualized in Figure 3-2. In order to compare these allocation methods, two properties are examined: efficiency and individual rationality.

Table 3-6 Profit allocation to each plant according to different methods

Locations	Stand-alone NPV	Profit allocated to each plant according to different methods (in thousand Canadian dollars)							
		Proportional		Shapley	Nucleolus	Separable and non-separable			EPM
		Stand-alone NPV	Volume of biomass used			ECM	ACAM	CGM	
Plant A	20,461	21,449	14,808	20,516	20,505	19,637	20,506	20,505	20,549
Plant B	213	224	361	1,552	1,524	1,958	1,556	1,543	229
Plant C	37,253	39,052	45,556	38,658	38,696	39,130	38,663	38,676	39,947
Sum	**57,929**	**60,726**	**60,726**	**60,726**	**60,726**	**60,726**	**60,726**	**60,726**	**60,726**

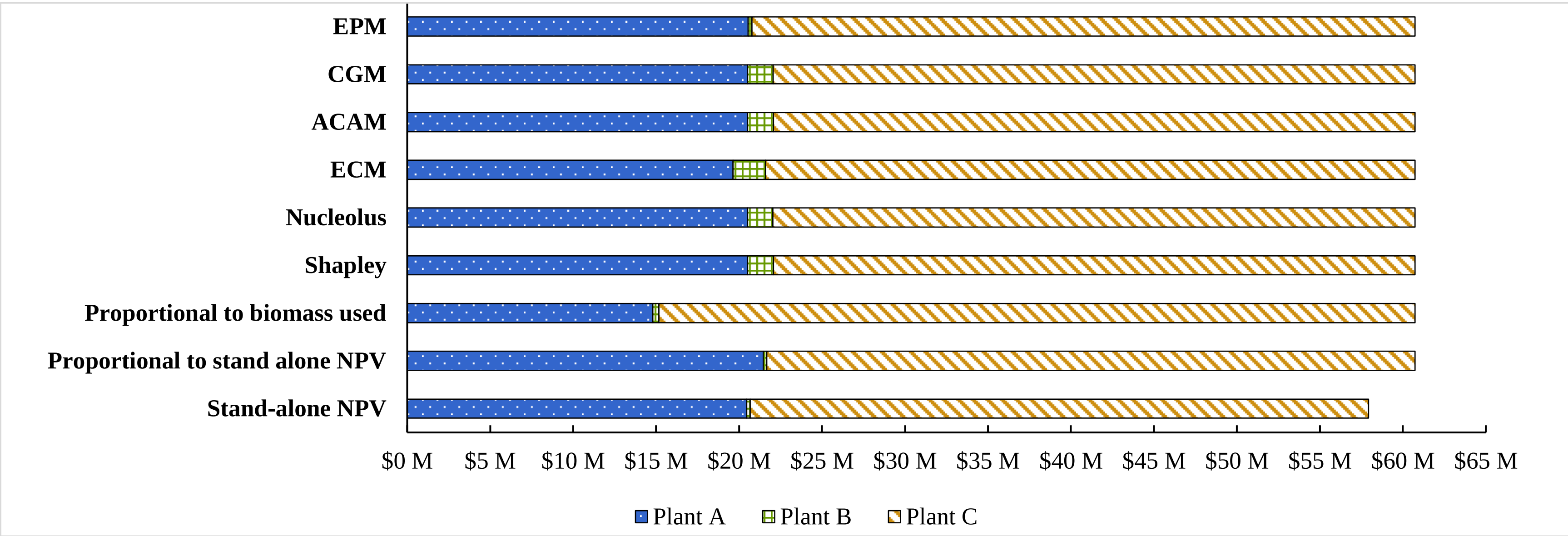

Figure 3-2 Profit allocation based on different methods

The efficiency property means that the total profit of the grand coalition, NPV_{C7}, should be allocated to the plants and nothing should be left over. By adding up the allocated profits to plants under each method, shown in the row "Sum" in Table 3-6, it is clear that every allocation method has a sum that is equal to NPV_{C7}. Consequently, these allocation methods all satisfy the property of efficiency.

To assess the property of individual rationality, two examples are given for illustration purposes. The first example is to examine whether the individual rationality of C1 is satisfied when the Shapley value is applied. When the plant in C1, which is plant A, chooses to work individually, it can earn a profit of about $20 million ($NPV_{C1}$). On the contrary, if plant A joins C7, the profit allocated to plant A by the Shapley method is around $21 million, which is higher than NPV_{C1}. Therefore, if plant A is rational, it should be willing to join C7 when the Shapley value is adopted. In other words, the individual rationality of C1 is fulfilled under the Shapley value.

The second example is to examine the individual rationality of C4 when the allocation is proportional to the volume of biomass used at the plant. The collaborated plants in C4, which are plants A and B, are able to generate about $20.7 million if only these two collaborate, referring to NPV_{C4} in Table 3-5. Plant A and plant B also have the option to join C7. If they do so, the total profit of these two plants in C7 is about $15 million, calculated by adding up the allocated profit to plant A ($14,808 thousand) and the allocated profit to plant B ($361 thousand) based on the "Volume of biomass used" in Table 3-6. It is obvious that plant A and plant B can get a higher profit in C4 than in C7, therefore they do not have the incentive to participate in C7, indicating that the individual rationality of C4 is not satisfied by this proportional allocation method. This comparison is conducted repeatedly for C1 to C6, and for each allocation method. If one method can fulfill both the efficiency and individual rationality properties, then this method is considered to be a stable allocation method.

Table 3-7 summarizes the stability of each allocation method. It is shown that the two proportional allocation methods and the ECM are not stable. The Shapley value, nucleolus, ACAM, CGM and EPM provide stable allocations, therefore these methods are recommended for the collaboration. Combining the results shown in Table 3-6 and Figure 3-2, it is observed that the Shapley value, nucleolus, ACAM, and CGM generate similar results, allocating about \$20.5 million to plant A, \$1.5 million to plant B, and \$38.6 million to plant C. Among these methods, the Shapley value is relatively more straightforward in terms of calculation, which is critical in the real-life applications.

The allocations to plant B and plant C given by EPM, however, differs significantly from the results given by the other methods. According to EPM, the profit allocated to plant B is approximately \$0.2 million, decreased by about 86% compared to that by other stable allocations, and most of this reduction is rewarded to plant C, the allocated profit of which increases from \$38.6 million to \$39.9 million. This result accords with the concepts behind EPM, which is to equalize the relative saving at each plant as much as possible. However, once plant B is aware of the fact that it has the potential to receive a much higher profit, plant B would be extremely reluctant to accept the results by EPM. In summary, if the three plants decide to collaborate, they would have to spend a great amount of time and effort on negotiation until they can find a compromise solution that satisfy everyone.

In addition to efficiency and individual rationality, it may also be helpful to investigate whether these allocation methods satisfy other properties introduced in Chapter 2. First, from Table 3-6 it is clear that each method only suggests one profit allocation plan, therefore they all fulfill the property of uniqueness. Also, since the labelling (A, B, C) is only used to distinguish plants and does not affect the allocation results, the property of anonymity is satisfied. The fulfillment of other properties such as symmetry, dummy player, and additivity cannot be assessed with the current case study.

Table 3-7 Stability property of the allocation methods

Characteristics	Allocation methods							
	Proportional		Shapley	Nucleolus	Separable and non-separable			EPM
	Stand-alone NPV	Volume of biomass used			ECM	ACAM	CGM	
Efficiency property	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Individual rationality property	No	No	Yes	Yes	No	Yes	Yes	Yes
Stability property	**No**	**No**	**Yes**	**Yes**	**No**	**Yes**	**Yes**	**Yes**

3.4 Conclusions

This chapter introduced a linear programming model to optimize the flow of forest-based biomass, starting from biomass supply points, through storage sites and bio-energy and bio-fuel conversion plants, to the final bio-product markets. The objective of the model was to maximize the NPV of the total profit that could be obtained by the whole supply chain, while considering the constraints mainly related to biomass supply, market demand, and conversion capacity.

The results of the optimization model indicated that this supply chain could generate a NPV of $61 million to be allocated among the three plants. Several allocation methods were adopted, and by assessing the properties of efficiency and individual rationality, it was recommended that the Shapley value, nucleolus, ACAM, CGM and EPM could be used as they provided stable allocation results. The Shapley value, nucleolus, ACAM, and CGM allocated about $20.5 million to plant A, $1.5 million to plant B, and $38.6 million to plant C, respectively, while EPM distributed $20.5 million to plant A, $0.2 million to plant B, and $39.9 million to plant C.

Chapter 4: Analysis of cost allocations and sensitivity analysis

4.1 Synopsis

The previous chapter presented the optimization model, which was aimed to maximize the NPV of the total profit that could be gained by different coalitions of plants. The model determined the optimal flow of biomass as well as the selection of conversion technologies at each plant. The results prescribed one biomass CHP boiler (2 MW) and one pellet mill (45000 tonnes/year) at plant A; a biomass gasifier (0.5 MW) at plant B; and one biomass CHP boiler (1 MW) and one pyrolysis plant (600 odt/day) at plant C. The optimized NPV was around $61 million when the three plants collaborated, which was more beneficial than plants operating individually without exchanging sawmill residues. The $61 million was allocated using different methods, and the Shapley value, the nucleolus, ACAM, CGM, and EPM were considered as stable allocations.

In this chapter, the collaboration is analyzed further. First, the relative saving at each plant is compared. Second, the revenue and cost of each plant in each coalition are evaluated, which can provide more insights about the impact of collaboration on bio-product generation and the biomass flow. Biomass flow is further investigated based on the proportion of sawmill residue used at each plant. Last but not least, the sensitivity of the NPV to bio-product price, bio-product market demand, forest residue price, forest residue availability, sawmill residue price, and discount rate is evaluated and discussed.

4.2 Analysis of relative saving at each plant

In Chapter 3, it was already observed that the allocations suggested by EPM and other methods varied, and this difference is further illustrated in Table 4-1. The table shows the relative saving at each plant when they collaborate in C7 and the listed stable allocation methods are applied. The relative savings of plants in other coalitions are not examined, as the stable allocations imply that the grand coalition C7 is the best coalition while no other coalition should be formed.

The relative saving is calculated using Equation (4-1):

$$Relative\ saving = \frac{Allocated\ profit - Stand\ alone\ profit}{Stand\ alone\ profit} \tag{4-1}$$

According to the Shapley value, nucleolus, ACAM, and CGM, the profit of plant A merely increases by around 0.2% after it joins the collaboration, which is not a strong motivation. The increase in profit for plant C (about 3.7%) is relatively more attractive. Contrary to plant A and plant C, plant B benefits considerably from the collaboration, the profit of which improves by an impressive percentage (620%). There are two reasons behind plant B's large relative saving. First, plant B's stand-alone profit is quite low, which makes a small denominator. Secondly, plant B has abundant sawmill residues, and the collaboration with other plants can help to sell the surplus sawmill residues and generate revenues.

Overall, the methods above all generate similar, but very uneven allocations. EPM, on the other hand, equalizes the relative savings of plant B and plant C. The reason why the relative saving of plant A is not equalized with the other two is that such allocation does not suffice the property of stability, but plant A still benefits from EPM as its profit increases compared to that by other allocation methods. Obviously, when the plants collaborate and negotiate for an allocation plan, plant A and plant C would benefit more if the EPM is applied compared to other methods.

Table 4-1 Relative saving at each plant

Plants	Relative saving at each plant compared to grand coalition using allocation methods				
	Shapley	Nucleolus	Separable and non-separable		EPM
			ACAM	CGM	
Plant A	0.26%	0.21%	0.22%	0.21%	0.43%
Plant B	625.72%	612.61%	627.84%	621.86%	7.23%
Plant C	3.77%	3.87%	3.78%	3.82%	7.23%

4.3 Analysis of revenue and cost at each plant

The profit distributed to each plant is decided by the adopted allocation method, and is the amount that each plant would receive in the collaboration. However, it is also worth investigating each plant’s profit when working with different partners, which can provide insights into the changes and impacts brought by collaboration. The profit gained at each plant is directly related to revenue and cost, which are retrieved from the optimization model presented in Chapter 3. A breakdown analysis of revenue and cost is conducted.

Table 4-2 and Table 4-3 show the revenue and the cost of each plant in different coalitions. In Table 4-2, the total revenue is segmented into seven components according to Equation (3-2). The savings from replacing fossil-based energy are calculated as the fossil energy cost multiplied by the total energy demand at the plant, which are both input parameters in the optimization model, therefore the value of this revenue component is the same in all coalitions. Revenue from selling power and selling heat are the revenues generated from selling the remaining amount of bio-energy to markets after the internal use. Similarly, revenues from selling pellets and selling bio-oil are those from selling bio-fuels to markets. Revenues from selling clean wood chips and selling hogfuel occur when plants cooperate, in this case one plant can earn revenues from selling sawmill residues to other plants.

In Table 4-3, the total cost is broken down into eight components based on the calculations shown in Equations (3-3) to (3-11). Note that as the investment cost and the fixed production cost are only dependent on the conversion technology type, they would not change regardless of the type of coalition. Therefore, these two components are excluded from the analysis, and the values in the columns do not add up to the total cost. The variable production cost is related to the plant's production level, which increases when more biomass is converted into bio-energy and bio-fuel. The costs of utilizing biomass at the plant is related to biomass purchase, preprocessing, transportation, and storage costs, and bio-product storage and transportation costs. The cost of fossil-based energy occurs when the bio-energy produced in the plant cannot fulfill the internal energy demand. More details will be given and the values in the two tables will be investigated in depth in the next section.

Table 4-2 Revenue breakdown for each plant

Plants in different coalitions		**Components of revenue (in thousand Canadian dollars)**							**Total revenue**
		Savings from replacing fossil-based energy	Sales of power	Sales of heat	Sales of pellets	Sales of bio-oil	Sales of wood chips	Sales of hogfuel	
Plant A	C1	23,793	4,482	-	60,700	-	-	-	88,976
	C4	23,793	4,474	-	60,990	-	0	0	89,258
	C5	23,793	4,484	-	60,700	-	474	2.6	89,455
	C7	23,793	4,482	-	60,700	-	319	0	89,296
Plant B	C2	4,185	48	-	-	-	-	-	4,234
	C4	4,185	48	-	-	-	58	0	4,292
	C6	4,185	119	-	-	-	1,195	102	5,602
	C7	4,185	119	-	-	-	1,195	102	5,602
Plant C	C3	316,361	-	9,933	-	274,536	-	-	284,786
	C5	316,361	-	9,933	-	276,079	0	0	286,328
	C6	316,361	-	9,933	-	275,698	0	0	285,948
	C7	316,361	-	9,933	-	276,659	0	0	286,908

Table 4-3 Cost breakdown for each plant

Plant in different coalitions		Components of cost (in thousand Canadian dollars)								Total cost
		Variable Production	Biomass Purchase	Biomass Preprocessing	Biomass Transportation	Biomass Storage	Product Storage	Product Transportation	Fossil-based energy	
Plant A	C1	16,228	500	8,335	4,384	27	0	17,071	0	68,514
	C4	16,285	558	8,331	4,523	27	0	17,153	0	68,846
	C5	16,228	527	8,798	4,688	36	0	17,071	0	69,319
	C7	16,228	518	8,641	4,583	32	0	17,071	0	69,044
Plant B	C2	2,096	0	0	0	0	0	0	0	4,020
	C4	2,096	0	0	0	12	0	0	0	4,020
	C6	2,096	14	237	80	1	0	0	0	4,354
	C7	2,096	14	237	80	1	0	0	0	4,354
Plant C	C3	31,801	2,330	38,842	68,660	88	178	1,078	40,212	247,533
	C5	31,950	2,792	38,592	69,194	89	126	1,084	40,437	248,685
	C6	31,920	3,555	37,617	67,866	90	175	1,082	40,370	247,020
	C7	32,009	3,864	37,437	68,204	91	143	1,086	40,505	247,682

4.3.1 Revenue and cost at plant A

As shown in Table 4-2, plant A can save about $24 million from replacing fossil-based energy with bio-energy in all coalitions. In addition, it experiences a growth in the sales of power, the sales of wood chips, and the sales of hogfuel when it only collaborates with plant C in C5. The main reasons behind this growth are: 1) in C5, plant A earns additional revenues by sending a portion of its sawmill residues to plant C; 2) plant A's own biomass demand can be fulfilled by purchasing harvesting residues and MPB residues, which have a higher yield ratio of heat and power as shown in Table 4-4.

Table 4-2 also indicates that as a result of collaboration, plant A would be able to generate more bio-energy for sale. In fact, plant A has the highest revenue in C5. When plant A collaborates with plant B in C4, despite the fact that its sales of pellet increased by about $0.3 million, plant A gets the lowest revenue compared to values in other coalitions, probably due to the declined sales of heat. As mentioned earlier, the heat converted at plant is assumed to be mainly used to fulfill the internal energy demand. As more pellets are produced in C4, the heat demand at the conversion facility increases, thus there is less heat available for sale. The income situation of plant A in C7 is almost the same as that in C1, except that in C7 plant A can sell wood chips.

Table 4-4 Biomass yield ratio

Plants	**Conversion technology**	**Bio-product**	**Yield ratio (GJ/odt)**			
			Harvesting residues	MPB logs	Wood chips	Hogfuel
Plant A	2 MW biomass boiler (CHP)	Heat	3.2318	3.2318	3.0141	3.0277
		Power	0.9696	0.9696	0.9042	0.9083
	45,000 tonnes/year pellet mill	Pellet	-	0.91	0.91	-
Plant B	0.5 MW biomass gasifier (Power only)	Power	1.0319	1.0319	0.9624	0.9667
Plant C	1 MW biomass boiler (CHP)	Heat	3.2370	3.2370	3.0189	3.0325
		Power	0.9711	0.9711	0.9057	0.9098
	600 odt/day pyrolysis plant	Bio-oil	0.607	0.648	0.656	0.492

The investment cost and fixed production cost at plant A is about $22 million in total, which is not shown in Table 4-3 as explained previously. According to Table 4-3, the variable cost of production is the same in C1, C5, and C7, yet slightly higher in C4, in which plant A converts more biomass into bio-products, as evidenced by the elevated sales of pellets in C4. The higher production level in C4 also leads to an increase in the cost of biomass purchase, biomass transportation, and product transportation as more biomass is bought and used, while the cost of biomass preprocessing reduces because in C4 plant A can purchase sawmill residues from plant B which does not require preprocessing.

It is also shown in Table 4-3 that when plant A collaborates in coalitions C5 and C7, compared to the situation in C1, it is faced with similar changes. As plant A sells sawmill residues to plant C in both C5 and C7, it must buy a larger amount of forest residues to maintain its own production, thus the costs of biomass purchase, preprocessing, and transportation rise. Also, unlike in C1 where the sawmill residues are considered "stored next door before use", when plant A collaborates in C5 or C7, it needs to keep more sawmill residues on site for future sales. Therefore, the biomass storage cost in C5 and C7 increases as well. To be more precise, the biomass storage cost of plant A in C7 is relatively lower than such cost in C5, because in C7 plant C prefers to buy sawmill residues from plant B due to the shorter distance.

4.3.2 Revenue and cost at plant B

In terms of the revenue and cost of plant B, it would save around $4 million by replacing fossil-based energy, which is the largest revenue component as described in Table 4-2. Collaboration of plant B with plant A in C4 increases the demand of sawmill residues slightly, which is reasonable, considering the unattractively long distance between these two plants. When plant B participates in C6 and C7, it can sell a large amount of sawmill residues to plant C, accounting for about 23% of its total revenue. Meanwhile, plant B would purchase forest residues, which have a higher yield in the selected biomass gasifier (Table 4-4), to produce power. Hence, participation of plant B in C6 or C7 also contributes to a growth in the sales of power.

Since plant B is installed with only one small scaled conversion technology, the investment cost and fixed production cost are as low as $2 million. From Table 4-3 it is observed that the variable cost of plant B is about $2 million in all coalitions, which means that the production level at plant B does not change no matter it collaborates or not. In C2 or C4, plant B does not purchase forest residues, indicating that in these two coalitions plant B is self-sufficient with its sawmill residues, while in C6 or C7 plant B spends a total of $0.3 million on purchasing, preprocessing, and transporting forest residues. The biomass storage cost rises as plant B joins the collaboration due to the same reason of keeping inventories for sales. It is noticed that plant B has the same income and expense in C6 and C7, because as long as plant C is in the coalition, plant B would not have any interaction with plant A, but would sell most of its sawmill residues to plant C.

4.3.3 Revenue and cost at plant C

As shown in Table 4-2, plant C's revenue goes up significantly when it participates in C5, C6 and C7, all benefiting from the increased sales of bio-oil. Among all the coalitions, C7 is the one with the largest sales of bio-oil, in which plant C is able to get a great amount of sawmill residues from both plant A and plant B. It is also revealed that as bio-oil is much more profitable than heat, when plant C has additional biomass, it will only be converted to bio-oil, while the production of heat does not expand. Table 4-2 shows that plant C has around $316 million savings through replacing fossil-based energy, however, this is not the real amount that plant C can save, and the reason will be explained later.

The optimization model prescribed one biomass CHP plant and one pyrolysis plant to be installed at plant C, especially the pyrolysis plant requiring high capital investment. Therefore, the investment cost and the fixed production cost at plant C add up to about $64 million. For other costs, Table 4-3 illustrates that the variable production cost, biomass purchase cost, and biomass storage cost increase when plant C collaborates and uses more biomass, while the cost of biomass preprocessing is lower because the used biomass is mainly sawmill residues. Plant C spends the least on biomass transportation in C6, because in this coalition it can take advantage of plant B located at a short distance to purchase sawmill residues from. The trend shown in the product transportation cost is in accordance with the changes in the sales of bio-oil, where plant C produces and sells most bio-oil in C5. Last but not least, it is noticed that unlike the other two plants, plant C has to pay for fossil-based energy, which is calculated using Equation (3-11). This illustrates that the produced bio-energy can only fulfill a portion of the total energy demand of plant C, and the benefits from replacing fossil-based energy in each coalition should subtract the cost of fossil-based energy. Therefore, plant C would save about $276 million on fossil-based energy cost.

4.4 Analysis of sawmill residues used at each plant

Since the collaboration among plants is defined as the exchange of sawmill residues, the amount of sawmill residues and the total biomass used at each plant are analyzed. Figure 4-1 shows the percentage of each biomass type that is used at each plant in different coalitions. Clearly, plant B does not purchase sawmill residues from others in any coalition. In other cases, namely plant A in C4 and plant C in C5, C6, and C7, the proportion of sawmill residues bought from other plants is always less than 5%. Because the supply chain is optimized, it is guaranteed that exchanging this amount of sawmill residue is the most profitable option for the plants in each coalition. This analysis indicates that even when the plants collaborate, the sawmill residues only provide a very small part of the required feedstock, while the majority is still forest residues. Therefore, the collaboration between plants will not significantly aggravate local road traffic and congestion or the associated pollution and nuisance from sawmill residue delivery trucks, which are listed as one of the major concerns hindering biomass utilization in communities (Rösch & Kaltschmitt, 1999; Upham & Shackley, 2007; Upreti & van der Horst, 2004; Wright, Dey, & Brammer, 2014). In addition, this small portion of sawmill residues has the potential to earn up to 7% more savings for the plants.

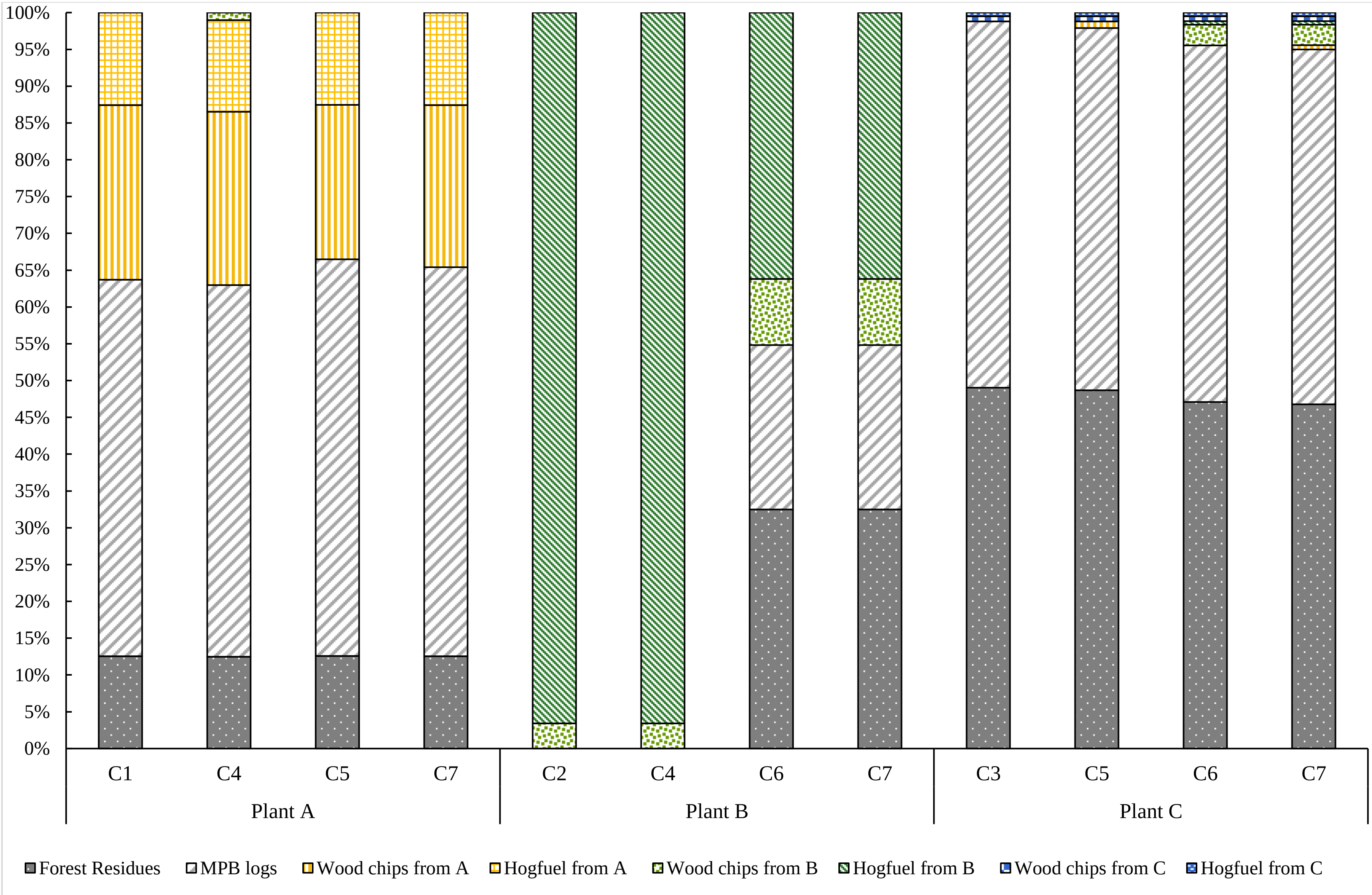

Figure 4-1 Proportion of each biomass type used at plant

4.5 Sensitivity analysis

4.5.1 Variations in NPV of the supply chain to parameter changes

In order to examine the variations of the optimal solution to the changes in optimization model input parameters, a sensitivity analysis was conducted and C7 was considered as the base case scenario. The studied parameters were: bio-product price, bio-product market demand, forest residue price (the costs of purchase and preprocessing), forest residue availability, sawmill residue price (the cost of purchase), and discount rate. These parameters were increased or decreased up to 50%. The values of some parameters are presented in Table 4-1, excluding heat market demand, electricity market demand, and forest residue availability which vary from month to month.

Table 4-5 Parameter values in sensitivity analysis

Parameter		Value in base case	Value (-50%)	Value (+50%)
Bio-oil price ($\$/m^3$)		266.4[a]	133.2	399.6
Pellet price ($/tonne)		160[b]	80	240
Heat price ($/MWh)		95[c]	47.5	142.5
Electricity price ($/MWh)		106.8[d]	53.4	160.2
Bio-oil market demand ($m^3/year$)		10176.2[d]	5088.1	15624.3
Pellet market demand (tonnes/year)		11250[c]	5625	16875
Forest residue price ($/odt)		24.7[d]	12.4	37.1
Sawmill residue purchase price ($/odt)	Wood chips	25[c]	12.5	37.5
	Hogfuel	10[c]	5	15
Discount rate (%)		10[e]	5	15

[a] Derived from (Marshall, Wu, Mun, & Lalonde, 2014)
[b] (Argus Media group, 2018)
[c] (Cambero, Sowlati, Marinescu, & Röser, 2015)
[d] (Akhtari et al., 2018)
[e] (Memişoğlu & Üster, 2016)

Figure 4-2 summarizes the results of the sensitivity analysis. The horizontal bars represent the variations in the NPV of the total profit compared to the base case. It is observed that the supply chain is most sensitive to changes in the bio-oil price. When it decreases by 50%, the total profit of the supply chain becomes negative and the collaboration turns infeasible. On the other hand, when the bio-oil price increases by 50%, the total profit doubles as plant C can make earn much more from selling bio-oil. The second most impactful change is the decrease in the bio-oil market demand, which lowers the amount of bio-oil that can be sold by the collaboration per year, while the increase in bio-oil market demand has no impact on the total profit due to the limited bio-oil production capacity at plant C. There is an inverse relationship between NPV and the discount rate, which ranks the third most sensitive parameter in Figure 4-2. Higher discount rate means cash flows that occur sooner in the time period are more influential to NPV. In this case study, since the earlier cash flows are mostly investment costs (cash outflows), when the discount rate increases, the investment costs take a more important role and the total NPV decreases. Some parameters like pellet price, forest residue price, and forest biomass (why residue/biomass) availability have intermediate impact on the supply chain profitability. Other parameters, such as pellet market demand and sawmill residue price, are not influential at all, which can be explained due to different reasons. For pellet demand, even if it is reduced by 50%, it is still far from being saturated with the amount of pellets that can be produced at plant A annually. As for the sawmill residue price, it can only influence the profit at individual plants. However, when it comes to the supply chain as a whole, the revenue from selling sawmill residues at one plant is exactly the cost of buying sawmill residues at another plant. Therefore, the revenue and the cost cancel each other out, and the total profit remains unchanged.

As mentioned above, it is shown in Figure 4-2 that some changes in parameters result in negative profits, namely the decreases in bio-oil price and bio-oil market demand. When bio-oil price or bio-oil market demand decreases by 50%, the reduction in the NPV of the total profit exceeds 100%, which does not make sense in real-life situations. Therefore, further calculation was necessitated to better define the range of changes in these parameters so that a positive NPV can be guaranteed.

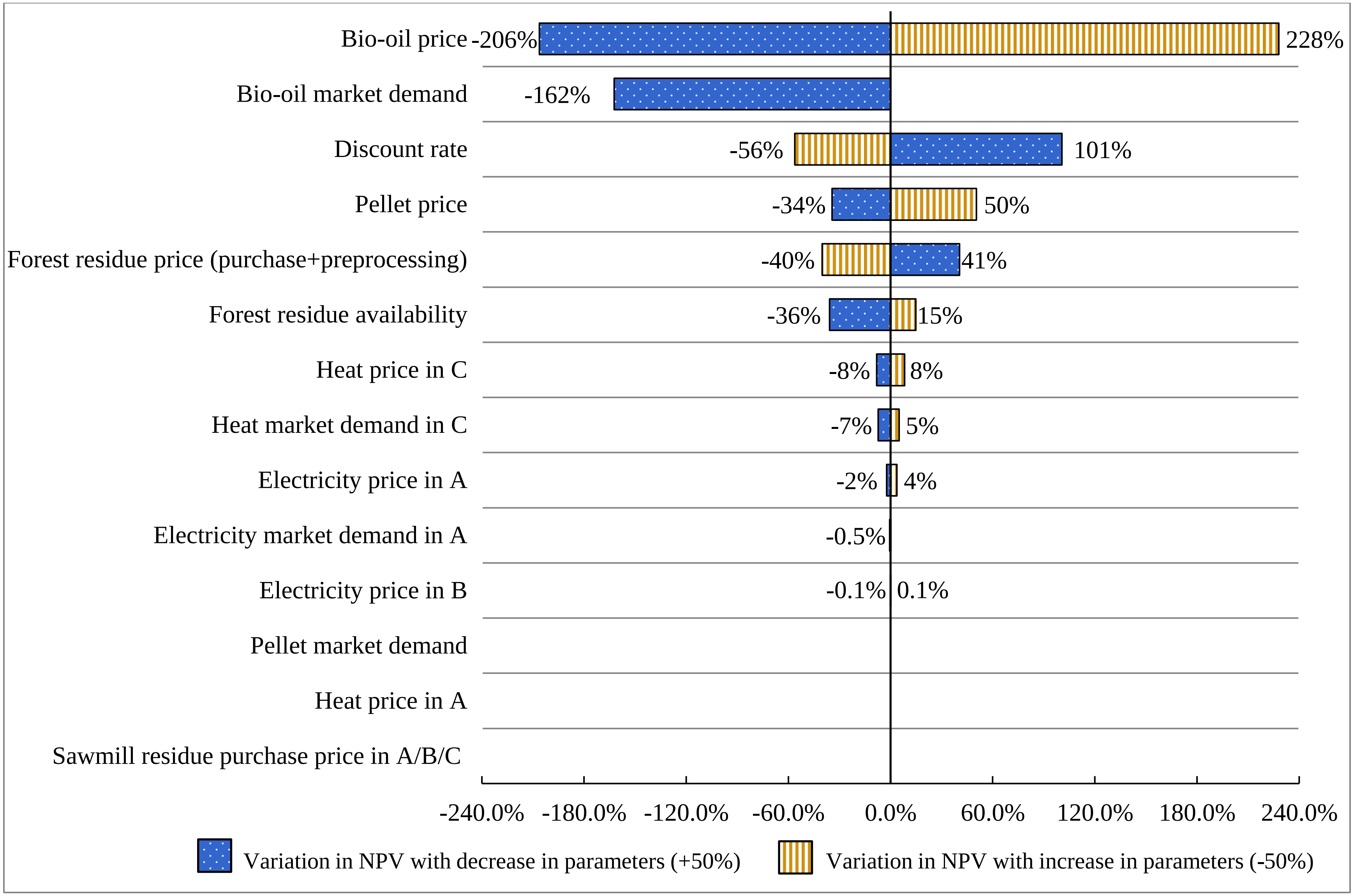

Figure 4-2 Percentage of variation in NPV with +50% and -50% change in parameters

4.5.2 Break-even analysis

A break-even analysis was conducted to find the points at which the changes in the parameters lead to a zero-profit supply chain. According to the sensitivity analysis, bio-oil price, bio-oil market demand and discount rate are the three parameters that the model is most sensitive to, therefore regression is used to accurately define the break-even points of these parameters.

Figure 4-3, 4-4, and 4-5 show the fitting results of regression between the NPV of the profit and the aforementioned parameters. Based on regression, the break-even point of bio-oil is -23%, which means that when the bio-oil price decreases by 23%, the supply chain is not able to make profits anymore. The break-even point is -36% for bio-oil market demand, and +120% for discount rate. The results prove that the supply chain's profitability closely depends on the market situation of bio-oil, and a fluctuation in bio-oil price can deeply sabotage the collaboration among plants. The change in discount rate is not as influential, which will not negate the profits of the collaboration until the rate increases to 22%.

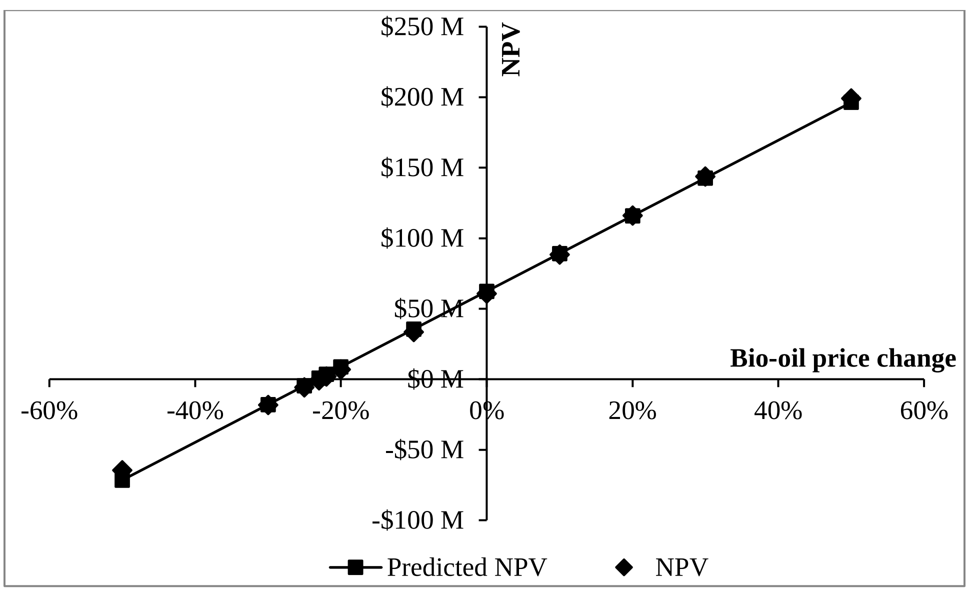

Figure 4-3 NPV and bio-oil price change fit plot

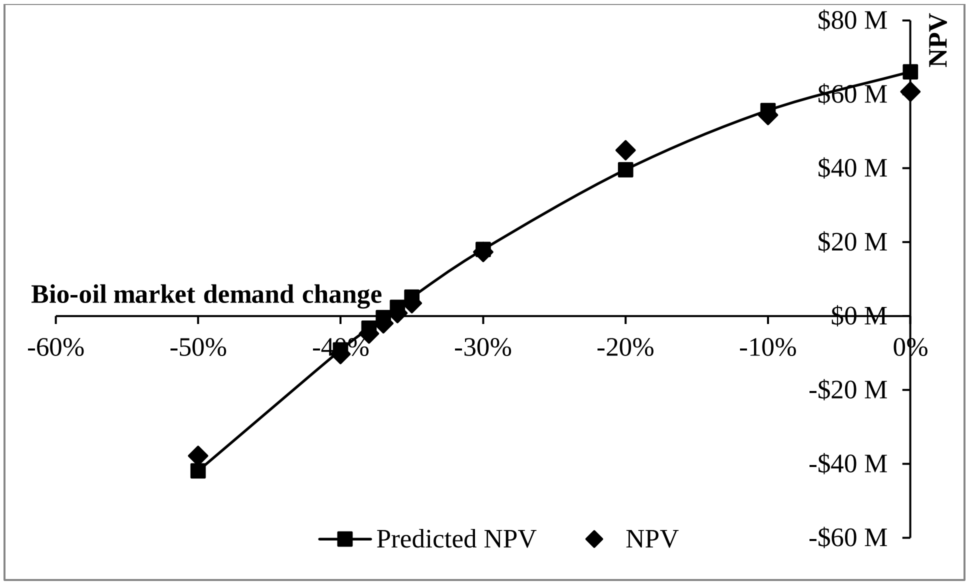

Figure 4-4 NPV and bio-oil market demand change fit plot

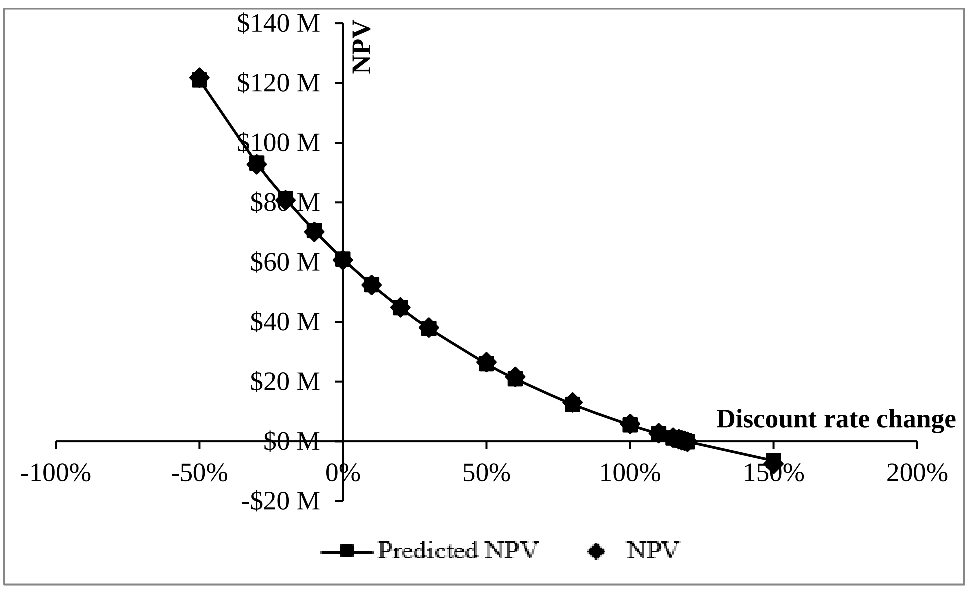

Figure 4-5 NPV and discount rate change fit plot

4.5.3 Sensitivity of profit allocation and relative savings in collaboration

The break-even points described in the previous section only consider the entire supply chain (C7), while the profit of individual plants (C1-C3) or a partial collaboration within the supply chain (C4-C6) may be negative, which is problematic in terms of profit allocation using the game theory methods. In order to address this concern, the break-even points were tested on coalitions C1 to C6, and it was found that C3's profit was negative at 23% reduction in bio-oil price. Consequently, knowing the break-even points are not enough to decide the feasible range of parameter changes. One approach that can be taken is to run the optimization model for C1 to C6 with changes in different parameter based on trial and error until finding a proper range that can guarantee a positive profit in every coalition.

After a series of trials, the ranges of changes in the following parameters were selected: bio-oil price can vary within ±10%, and the other influential parameters including bio-oil market demand, discount rate, pellet price, and forest biomass price can change within ±20%. The reason is that 10% change in bio-oil price can assure positive profits, whereas 20% change cannot, therefore different ranges of variation are adopted as needed. Using these ranges, the sensitivity of profit allocation to the changes in parameters are examined.

Table 4-6 presents the impact of parameter changes on the stability of profit allocation. The row "base case" shows the stability of the allocation methods without changing any parameter, followed by the rows with all changes that can increase the total NPV, then the rows with all changes to decrease the total NPV. In the base case, as discussed in the previous chapter, the two proportional allocation methods and ECM are not stable, and they never generate stable results in any of the scenarios. The nucleolus, ACAM, CGM, and EPM are always stable regardless of the parameter changes. The stability of the Shapley value, however, depends on the parameters. When the bio-oil price drops by 10% or the bio-oil market demand decreases by 20%, the Shapley value is no longer stable. In other words, in this study the Shapley value cannot guarantee stability, which is in accordance with the observations in previous research (Conitzer & Sandholm, 2004).

Table 4-6 Stability of allocation methods to parameter changes

Scenarios	Allocation methods							
	Proportional		Shapley	Nucleolus	Separable and non-separable			EPM
	Stand-alone NPV	Volume of biomass used			ECM	ACAM	CGM	
Base case	Not Stable	Not Stable	Stable	Stable	Not Stable	Stable	Stable	Stable
Bio-oil price +10%	Not Stable	Not Stable	Stable	Stable	Not Stable	Stable	Stable	Stable
Bio-oil market demand +20%	Not Stable	Not Stable	Stable	Stable	Not Stable	Stable	Stable	Stable
Discount rate -20%	Not Stable	Not Stable	Stable	Stable	Not Stable	Stable	Stable	Stable
Pellet price +20%	Not Stable	Not Stable	Stable	Stable	Not Stable	Stable	Stable	Stable
Forest residue price -20%	Not Stable	Not Stable	Stable	Stable	Not Stable	Stable	Stable	Stable
Bio-oil price -10%	Not Stable	Not Stable	Not Stable	Stable	Not Stable	Stable	Stable	Stable
Bio-oil market demand -20%	Not Stable	Not Stable	Not Stable	Stable	Not Stable	Stable	Stable	Stable
Discount rate +20%	Not Stable	Not Stable	Stable	Stable	Not Stable	Stable	Stable	Stable
Pellet price -20%	Not Stable	Not Stable	Stable	Stable	Not Stable	Stable	Stable	Stable
Forest residue price +20%	Not Stable	Not Stable	Stable	Stable	Not Stable	Stable	Stable	Stable

Since the values of parameters have changed in each scenario, the relative saving of each plant needs to be recalculated.

Table 4-7 shows the variations in plant A's relative saving resulted from parameter changes. There are two empty cells in the column "Shapley", because in these two scenarios the Shapley value cannot give stable allocations and is excluded from the analysis. According to the table, Plant A is most sensitive to the changes in pellet price, as the sales of pellets contribute to over half of its revenue. Its relative saving is even higher when pellet price reduces by 20%, mainly for two reasons. First, it arises from the way that relative saving is calculated. When the pellet price drops, plant A has a low stand-alone profit, making a small denominator. Besides, the decreased profitability of pellets highlights the importance of sawmill residues sales, which partly compensates the reduced revenue from pellets. It is also observed that as the price or the demand of bio-oil decreases, the relative saving at plant A becomes zero, because in these two scenarios plant A does not sell sawmill residues to plant C anymore. When plant A has no contribution to the collaboration, it should not be rewarded with additional profit.

Based on Table 4-8, plant B is most sensitive to discount rate changes, due to similar reasons. Plant B has a very low stand-alone profit, which is a small denominator and amplifies the impact of fluctuations in the discount rate, while this impact can be largely mitigated by the application of EPM in profit allocation. Plant B is also sensitive to the decrease in forest residue price and bio-oil demand. In the base case scenario, plant B is able to sell a great amount of sawmill residues to the bio-oil conversion facility in plant C, accounting for the largest portion of plant B's total revenue. If forest biomass price decreases or bio-oil demand decreases, the demand of sawmill residues from plant C will be less, which affects plant B negatively.

As shown in Table 4-9, plant C is very sensitive to bio-oil price changes, since over 90% of its total revenue is obtained from the sales of bio-oil. However, as explained previously, the capacity of bio-oil production is already fully utilized in the base case scenario. Hence, even if the market demand is expanding, plant C is not able to generate extra profit by producing more bio-oil.

Another noteworthy fact that can be observed from the three tables is that in all scenarios, EPM allocates equal relative savings to plant B and plant C, the amount of which is much larger than that of plant A. The reason is that plant B and plant C contribute more to the collaboration in terms of the amount of sawmill residues that are exchanged.

Table 4-7 Relative saving of plant A to parameter changes

Scenarios	Allocation methods				
	Shapley	Nucleolus	Separable and non-separable		EPM
			ACAM	CGM	
Base case	0.3%	0.2%	0.2%	0.2%	0.4%
Bio-oil price +10%	0.4%	0.3%	0.3%	0.3%	0.6%
Bio-oil market demand +20%	0.3%	0.2%	0.2%	0.2%	0.4%
Discount rate -20%	0.2%	0.2%	0.2%	0.2%	0.4%
Pellet price +20%	0.2%	0.1%	0.1%	0.1%	0.3%
Forest residue price -20%	0.3%	0.2%	0.2%	0.2%	0.5%
Bio-oil price -10%	-	0.0%	0.0%	0.0%	0.0%
Bio-oil market demand -20%	-	0.0%	0.0%	0.0%	0.0%
Discount rate +20%	0.3%	0.3%	0.3%	0.3%	0.5%
Pellet price -20%	0.8%	0.7%	0.7%	0.7%	1.4%
Forest residue price +20%	0.2%	0.1%	0.1%	0.1%	0.3%

Table 4-8 Relative saving at plant B to parameter changes

Scenarios	Allocation methods				
	Shapley	Nucleolus	Separable and non-separable		EPM
			ACAM	CGM	
Base case	626%	613%	628%	622%	7%
Bio-oil price +10%	633%	614%	637%	626%	4%
Bio-oil market demand +20%	626%	613%	628%	622%	7%
Discount rate -20%	328%	322%	329%	326%	6%
Pellet price +20%	627%	617%	630%	624%	7%
Forest residue price -20%	572%	555%	575%	567%	5%
Bio-oil price -10%	-	596%	596%	596%	25%
Bio-oil market demand -20%	-	486%	487%	486%	9%
Discount rate +20%	10171%	9940%	10206%	10104%	9%
Pellet price -20%	622%	603%	625%	617%	7%
Forest residue price +20%	676%	669%	677%	674%	10%

Table 4-9 Relative saving at plant C to parameter changes

Scenarios	Allocation methods				
	Shapley	Nucleolus	Separable and non-separable		EPM
			ACAM	CGM	
Base case	4%	4%	4%	4%	7%
Bio-oil price +10%	2%	2%	2%	2%	4%
Bio-oil market demand +20%	4%	4%	4%	4%	7%
Discount rate -20%	3%	3%	3%	3%	6%
Pellet price +20%	4%	4%	4%	4%	7%
Forest residue price -20%	3%	3%	3%	3%	5%
Bio-oil price -10%	-	13%	13%	13%	25%
Bio-oil market demand -20%	-	5%	5%	5%	9%
Discount rate +20%	5%	5%	5%	5%	9%
Pellet price -20%	4%	4%	4%	4%	7%
Forest residue price +20%	5%	5%	5%	5%	10%

4.6 Conclusions

This chapter presented analyses of relative savings, revenues and costs, and feedstock composition of each plant when they collaborate in different coalitions, and also discussed the sensitivity of the NPV to bio-product price, bio-product market demand, forest residue price, forest residue availability, sawmill residue price, and discount rate. Important findings are listed below.

a) The relative savings of the three plants were very unbalanced according to most of stable allocation methods, ranging from 0.2% to 627%, whereas when EPM was adopted, the relative savings of plants were equalized and the range was narrowed down to 0.4%-7%.

b) According to the revenue and cost analysis, the savings from fossil-based energy accounted for a very important part in each plant's total revenue, and the sales of bio-fuel, namely pellets and bio-oil, also contributed a large portion to the revenues at plant A and plant C. When it came to costs, the investment costs took the biggest share in the total costs of all plants, except for plant C where the cost of biomass transportation was ever higher, as plant C used much more biomass than the other two plants.

c) As sawmill residues only accounted for less than 5% of the total biomass feedstock at each plant, the collaboration among plants would not put more stress on local road traffic or intensify the problems of pollution and nuisance from sawmill residue delivery trucks.

d) The sensitivity analysis indicated that the supply chain was most sensitive to changes in the bio-oil price, 23% deduction of which would result in zero profit of the collaboration. The changes in bio-oil price and bio-oil market demand would also impact the stability of allocation based on the Shapley value.

Chapter 5: Conclusions, limitations, and future research opportunities

5.1 Summary and conclusions

This thesis examined the benefits of collaboration and conducted profit allocation in a case involving three bio-product conversion plants located in British Columbia. To do so, a linear programming model was developed to optimize the forest-based biomass supply chain, and the maximum profit of the supply chain was distributed to plants using different game theory allocation methods.

The game theory allocation methods introduced in Chapter 2 requires the establishment of both the grand coalition that contains all the possible participants, and sub-coalitions that involve only some of the participants. Therefore, in this study, seven different coalitions denoted as C1 to C7 were set up according to different partnerships among the three plants. C7 included the collaboration of all three conversion facilities in the supply chain.

In Chapter 3, a linear programming model was developed based on (Akhtari et al., 2018) to determine the optimal flow of biomass from supply points to the conversion plants in each period, the optimum amount of bio-products to produce in each period, the optimum storage of biomass and bio-fuels in each period, and the type of conversion technology at each plant. The conversion plants denoted as plant A, plant B, and plant C could earn revenues from the sales of bio-products, the savings by replacing fossil-based energy, and the sales of spare sawmill residues from one conversion plant to another conversion plant. At the same time, they also had to pay for the costs of biomass purchase, preprocessing, transportation and storage, as well as the costs of investment, production, bio-product storage and transportation, and fossil-based energy if the produced bio-energy was not enough to cover the entire internal energy demand. The objective of the optimization model was to maximize the net present value of (NPV) of the total profit of the conversion plants, subject to the constraints on biomass supply, bio-product market demand, and conversion capacity. The results of the optimization model indicated that the maximum NPV is about $61 million when the three plants collaborate. The optimal solution also illustrated that plant A should install one biomass CHP boiler (2MW) to meet internal bio-energy demand,

and one pellet mill (45,000 tonnes/year) for export market sales. Plant B should have a biomass gasifier (0.5 MW) to produce electricity. Plant C should be equipped with a biomass CHP boiler (1MW) and a pyrolysis plant (600 odt/day). In order to assure the comparability, the selected technology type was not allowed to be changed when plants form sub-coalitions. Then, the optimization model was used to determine optimum solution for the sub-coalitions one at a time to lay the foundation for profit allocation.

The profit allocation results proved that the collaboration of three plants would generate the highest NPV of the total profit, which was $3 million more than the sum of the profits obtained by three plants operating individually. The total profit was then distributed to plants according to the following allocation methods: two proportional methods based on stand-alone profit and volume of biomass used, the Shapley value, the nucleolus, ECM, ACAM, CGM, and EPM. By evaluating the properties of efficiency and individual rationality, it was revealed that the proportional methods and ECM did not generate stable allocations, therefore these methods should not be adopted. Among the stable methods, the Shapley value, the nucleolus, ACAM, and CGM generated similar results, allocating about $20.5 million to plant A, $1.5 million to plant B, and $38.6 million to plant C. On the contrary, the allocations to plant B and plant C given by EPM considerably differed due to its nature. According to EPM, the profit allocated to plant B was approximately $0.2 million, decreased by about 86% compared to that in other stable allocations, and most of this reduction was rewarded to plant C, the allocated profit of which increased from $38.6 million to $39.9 million. As the consequence of this difference, if the plants decided to collaborate, they would have to spend time and effort on negotiation until they could find a compromise solution that could satisfy everyone.

Chapter 4 presented further analysis of results and the sensitivity analysis. By analyzing the revenues and costs at each plant, it was revealed that plant A and plant C would make the largest portion of revenues through the sales of pellets and bio-oil, while plant B would rely on the sales of sawmill residues. As the collaboration was defined as the exchange of sawmill residues, plant B played an important role in this study and was rewarded with a high relative saving. In addition, another impact of collaboration was that when plants collaborated, they tended to store more sawmill residues on site in advance in order to fulfill future sales.

According to the sensitivity analysis, the collaboration of the three plants was most sensitive to the fluctuations in bio-oil price. When the bio-oil price decreased by 23%, the supply chain was no longer profitable. The reason behind this impact was that the production of bio-oil was the most profitable bio-product conversion option in this collaboration, accounting for over 70% of the supply chain's total revenue. However, it is worth noting that pyrolysis technology is still undergoing the process of development (Dabros et al., 2018; Hu & Gholizadeh, 2019). In Brown, Thilakaratne, Brown, & Hu, (2013), it was mentioned that no commercial-scale fast pyrolysis facilities were being constructed by the year of 2010. Moreover, the innovation and development of bio-fuel is strongly affected by the price of crude oil, and it may be discouraged as the result of the recent falls in the crude oil price (Guillouzouic-Le Corff, 2018). In order to promote the commercialization of bio-oil, several pilot demonstration plants have been established, including Fortum Bio-oil plant in Finland (started construction in 2012), bioCRACK in Austria (2012), Green Fuel Nordic Biorefinery in Finland (2012), NER300 projects in Estonia and Latvia (2014), Ensyn Pyrolysis in Canada (2014), and Empyro Fast Plyrolysis Plant in Netherlands (2015).

In addition to bio-oil price, the collaboration was also sensitive to other parameters included bio-oil market demand, discount rate, pellet price, and forest biomass price. Changes in these parameters might affect the stability of allocation methods, as the Shapley value became unstable when the bio-oil price dropped by 10% or the bio-oil market demand decreased by 20%.

5.2 Limitations

In this study the collaboration was defined as the trade of sawmill residues at constant prices, which may not be the case in reality. For example, sawmill residues which are cleaner or have lower moisture content can usually fetch better prices, and some sawmills may even offer volume discounts for facilities with large-scaled production. The optimization model in this thesis, however, did not incorporate these variations.

Another limitation is with respect to the sales of bio-product. In this case study plant A converts biomass to heat and electricity mainly for internal use, and the surplus electricity is sold to nearby communities. From this point of view, plant A can be considered as an independent power producer (IPP) who sells clean energy to BC hydro. According to the regulations, currently BC hydro only accepts electricity from community-scale electricity projects that have an aggregate capacity of no more than 1 MW (BC Hydro, 2018), while the capacity of plant A is 2MW, which is well above the limit. In addition, BC hydro has several electricity purchase agreements under review at this time, and has suspended accepting new IPP applications until the review is completed with government. Therefore, selling bio-power to BC hydro is not a feasible option at the time being, which necessitates reconsideration on the conversion technology type and capacity at plant A in real conditions.

Last but not least, the numerical results of this study was largely dependent on the estimated data related to biomass supply and costs and bio-products demand and prices, while the possible changes in the supply and demand, which could be caused by recent disturbances such as wildfires and BC’s increasing carbon tax, were not incorporated. However, it should be noted that the intention of this study was not to suggest actual investments in bio-energy and bio-fuel conversion technologies. Instead, the focus of this work was to examine different allocation methods, which could provide some insights for the forestry industry, especially regarding the use of proportional allocation. Also, this work indicated that the profitability of bio-energy and bio-fuel supply chains was very sensitive to the market situation of bio-products. Policy makers should be aware of this when promoting the use of biomass for energy generation, and a detailed market analysis is strongly recommended.

5.3 Future work

It was noticed from the revenue and cost analyses that the distances between conversion facilities had a great impact on the sawmill residue flows, which was not directly reflected in the profit allocation. Therefore, one research topic that can be investigated in the future is the intangible benefits of collaboration, including but not limited to the growth in geographic coverage, the access to different markets, and the improvement in service levels. Although it is difficult to share them in monetary terms, the value of these benefits can be reflected in the allocation method, for example, by assigning a larger part of savings to partners who have the biggest contribution in completing the geographical coverage.

In this work, the supply chain partners were expected to be cooperative with a common goal to maximize the total profit of the whole supply chain, therefore the collaboration of partners was assumed to be the starting point of the modeling. The future work can integrate optimization models with considerations of fair profit allocation, so that such models can facilitate decisions on the design of the supply chain and the formation of the collaboration simultaneously.

Besides, it should be noted that partners in the collaboration are usually different in size. The larger ones, such as plant C in this case, is likely to lead the collaboration and to demand more benefits to be allocated to themselves. As mentioned in (Audy et al., 2007), the leader's opportunistic behavior may sacrifice the profit of non-leading participants, in which case the collaboration cannot obtain all the attainable benefits. In order to avoid this situation, participants can initiate negotiations. The strategies and behaviors of the supply chain partners and their negotiation process are frequently analyzed in the approach of non-cooperative game theory, an extensive review of which is provided in (Cachon and Netessine 2006), and the application of this approach in forestry is an interesting research opportunity.

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Appendix A: An example of NPV calculation

NPV represents the time value of money. It is a widely used concept to evaluate and compare profitability of financial investments. This appendix shows how the NPV is calculated based on future cash flows. For illustration purposes, the calculation of NPV_{C1}, which is the NPV of coalition C1 (the stand-alone coalition of plant A) is shown below.

The planning horizon considered in this study is 20 years. The initial investment cost of plant A can be calculated by the second term in Equation (3-1), and the annual revenue and annual cost can be calculated based on Equation (3-2) to Equation (3-11). Once the calculation is done, the cash inflows and outflows of plant A in each year can be obtained as shown in Figure A-1.

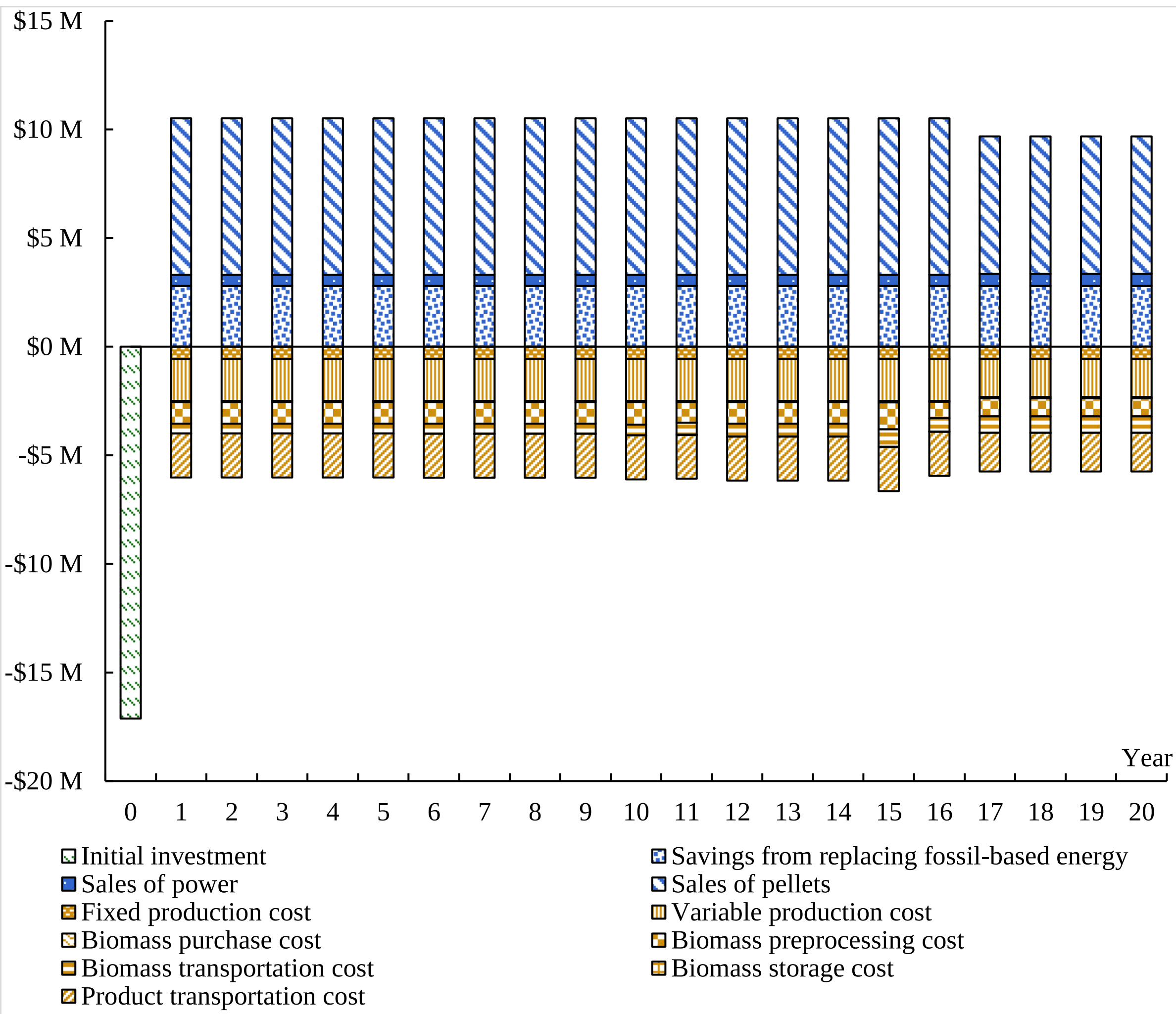

Figure A-1 Cash flows of plant A in coalition C1

In Figure A-1 it is noticed that the cash flows are relatively steady from year 1 to year 20, while at the beginning of the planning horizon, a great amount of cost is incurred from the investment and installation of conversion technologies.

Given the cash flows and the assumed discount rate (10% in this study), the NPV of C1 can be calculated according to Equation (A-1).

$$NPV = \sum_s \frac{Revenue_s - Cost_s}{(1+IR)^s} \quad \text{(A-1)}$$

The investment cost occurred in the beginning ($s = 0$) does not need to be discounted because it is already the current value at time 0, while profits in future years ($s = 1,2,3 \ldots 20$), which are obtained by subtracting annual cost from annual revenue, are converted into the present value based on the chosen discount rate IR.