

A MIXED INTEGER MATHEMATICAL MODELLING FRAMEWORK FOR  
INVESTIGATING APPROACHES TO STRATEGIC FOREST NETWORK CAPACITY  
DESIGN

by

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تقدیم بہ کسانی کہ بہ من آموختند:

بہترین دوستم: مادرم

بزرگترین استادم: پدرم

*To those who have taught me:*

*My best friend, my mother*

*My greatest teacher, my father*

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## Abstract

Different elements in the forest industry, such as available forest resources, manufacturing plants and mills, and potential customers constitute links in a value chain. Strategic forest network design deals with optimizing the potential performance of this chain. In the forestry network, although some of the decisions are made independently they may have high impact on each other. These consist of forest management, capacity expansion, and network flow problem.

Considering forest management and the network design problems including capacity expansion, we can address two approaches to deal with them. The first approach, which is the current approach in Canada, is the separate approach in which the forest management is done as a separate decision making process. In the second approach, which is an integrated approach, the forest management problem is considered as a part of the network design problem and in a single decision making process. The goal of the present research is to investigate these two decision making approaches, using mathematical models and laboratory data sets.

Although the results cannot be extended to reality, they provide analysis regarding the dependence of different decisions in forestry. In all the test cases we have investigated, the integrated approach gives a consistent advantage over the separate approach. The result of this research can give valuable insight to have an efficient strategic decision making in forestry.

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# Chapter 1: Introduction

## 1.1. Background

Canada's forest industry is among the largest in the world, with 10% of world forests. Importantly, forestry made a 1.9% contribution to Canada's GDP in 2010 and is responsible for 1.3% of employment [1]. Decisions made about this important natural resource have significant environmental, social, and economic effects. There are many risks in the forest industries market. These include the uncertainty in current and future product demand and price or new emerging products such as bio products and other highly value added products. One of the ways to mitigate the risks is an efficient network design.

Different elements in the forest industry, such as available forest resources, manufacturing plants and mills, and potential customers, constitute links in a value chain. Strategic forest network design deals with optimizing the potential performance of this chain. A multitude of highly integrated elements, a dynamic environment, and uncertainty about prices are three important characteristics of this network. Although the overall forest system is highly integrated, there are many different possible design decisions that are often made independently through this network by different decision makers. These decisions

may have consequences for the whole system and other decision making processes. Some of these decisions deal with finding long-term answers to a common set of design questions in the forestry network such as:

- What types of mills and how many of them should be established or expanded?
- Where should new mills be located?
- How do we procure raw materials over time from the forests? In other words, how should we manage the forests?
- How much of each product should be produced and how should materials flow through this network?

These questions can be understood in terms of three interconnected problems. The first is the capacity planning problem, which is typically dynamic, depending on anticipated product markets and on raw material availability. The first and second questions relate to this issue. The second problem pertains to forest management and how to harvest the forest, which is addressed by the third question. The third problem is the network flow problem, which is mostly affected by forest product availability, harvest, transportation, and production costs, and market demands and prices. The fourth question deals with the network flow problem.

The goal of the present research is to compare different decision making approaches in an integrated forest value chain to find answers for the aforementioned problems through examining their solutions. The result of this research will be used to discuss the necessity of an integrated decision making process to find strategic options for integrated industry capacity in a network design context which are consistent with forest management and final products' market.

## 1.2. Forestry network

A forestry network consists of many supply chains interacting with each other. As raw materials from the forest go through this network, they gradually transform into many products. This divergent manufacturing network is characteristic of the forest industry. Figure 1 shows a simplified overview of the forestry network.

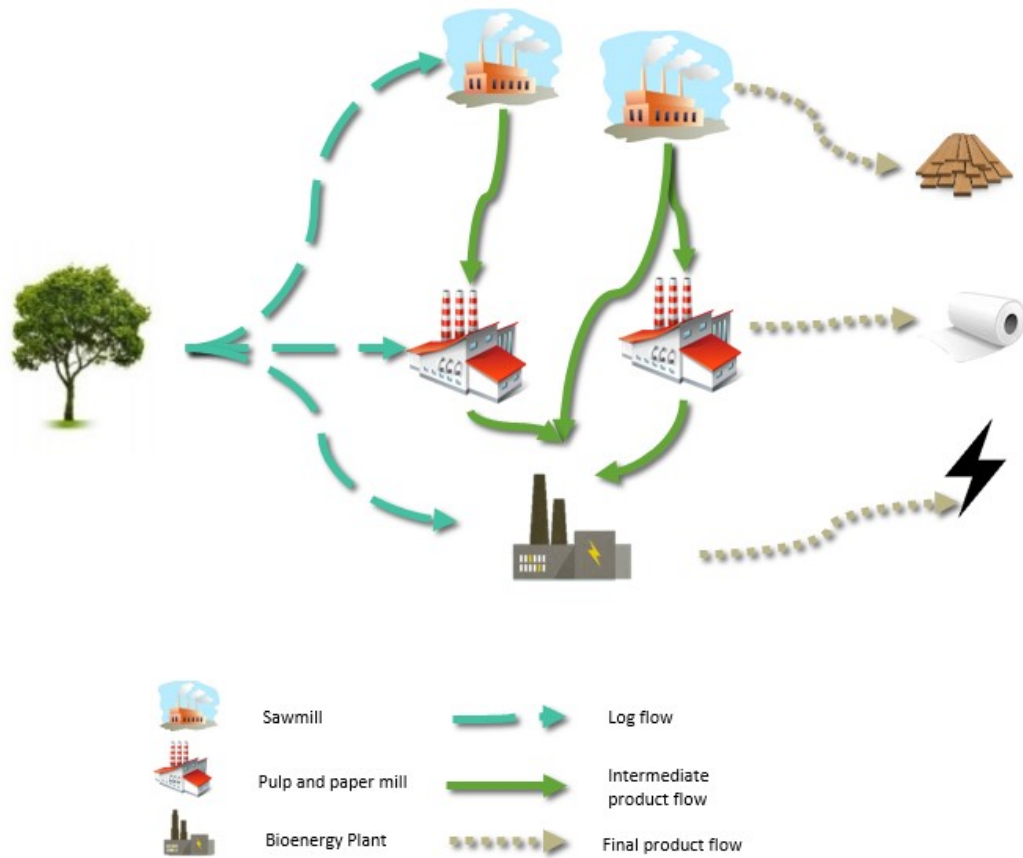


Figure 1: General overview of the forestry network in this research

As we can see in Figure 1, there is a web of different elements. These elements can be categorized as supply chains such as Pulp and Paper supply chains, Panel and Engineered Wood supply chains and Bio-fuel supply chains [2]. In reality, these chains are much more complex. These chains are connected and interact with each other. To consider the overall expansion for the network, all of these elements and their interactions should be taken into account. The first connection between these supply chains is the forest. The forest provides log and raw material for all supply chains. The second is the by-products which can be sent from one mill as an input to other mills. For example wood chips from sawmills can be used in pulp mills as an input material.

As the starting point in this network, the forest supplies the raw materials to all branches. The forest is harvested and transformed, and its several products flow through

this network. Different products from the forest, including different types of logs, are sent to different mills.

One of the main supply chains in this network is the lumber, panel and engineered wood supply chain, in which the main mills are the saw mills and panel mills. The inputs for these mills are logs and the outputs are lumber and other engineered wood products. There are also by-products, such as chips, which can be sent to pulp mills, and bark, which can be used to produce energy.

The next important supply chain in the forestry network is the pulp and paper supply chain, in which the input products are the logs and the chips from sawmills. Although the main products of these mills are pulp and paper, their by-products such as bark and chips can be used to generate energy in the same plant or in heating plants [2].

The last supply chain is the bio fuel chain, which uses the forest residue and other plant by-products, such as barks and chips, to produce energy and electricity [2].

The products from the first two supply chains can go through a number of converting plants and distribution centers to reach the final customers who are not studied in this research. Energy can also be introduced as one of the products of the system. Due to the divergent nature of the network, each plant has a set of recipes. Each recipe specifies the amount of each of output product that can be produced from one unit of input product.

All of these sets of aforementioned supply chains and elements interact with each other and constitute a value chain. Having a more exact view on each individual element, the interactions are more complex than simple linkages. Therefore, considering all interactions, the system acts more like a web. Although the forestry network, which is studied in this research, is a simplified version of the actual network, the three supply chains and their interaction are taken into account in this research. How to define strategic decisions to design this integrated network is the main subject of the thesis. Since all production starts at the forest, there are both competitive and complementary issues in the forest economy; this raises the question whether the current decision making process, in which the forest management process is done separately from the rest of the network, is

logical or not. Are there advantages and disadvantages of having an integrated decision making process over a separate one?

### 1.3. Research objectives and questions

Considering the forestry network, the production facilities are the core of this system. Decision making about investment in new capacities on one hand depends on forests as the supply where availability dynamically varies over time and space, and on the other hand, depends on the final products' demand and price. As previously mentioned, the main objective of this research is to investigate strategic decision making approaches for an efficient network design and capacity investment in an integrated forest industry which is consistent with forest management and final products' market.

In the forestry network, although some of the decisions are made independently they may have high impact on each other. For example, a main set of decisions involve forest management; specifically when, where and how to harvest forests. The results of forest management will have major impact on other decisions in the network including capacity investment strategies. As described in the section 1.1, there are three categories of question that should be answered in the strategic forestry network design problem. These consist of forest management, capacity expansion, and network flow problem (Figure 2).

The main question of forest management is how to harvest forests in a sustainable and profitable way. Forest consists of different stands. Each stand has a set of characteristics including age, cover, and stocking. Based on its current situation, stands start with an initial state. How a stand will be managed over time will be defined by a prescription assigned to it. Each scheme of management is referred to a prescription. To accomplish various ecological and economic goals for the overall system and satisfy different constraints, stands are assigned to one of several prescriptions.

In the capacity expansion problem, the problem is to know what type of capacity, at what size, and where should be installed. There are important interconnected issues regarding this problem which should be taken into account. The economies of scale in capacity installation and operating costs result in bigger sized plants. This may increase the transportation cost. Types of interaction between facilities also plays an important role.

Some are economically competitive, such as two pulp mills, some may be economically complementary, such as sawmills and pulp mills. Locations of these mills are also another important issue capacity expansion.

Considering forest management and the network design problems including capacity expansion, we can address two approaches to deal with them. The first approach, which is the current approach in Canada, is the separate approach in which the forest management is done as a separate decision making process. In the second approach, which is an integrated approach, forest management problem is considered as a part of the network design problem and in a single decision making process (Figure 3).

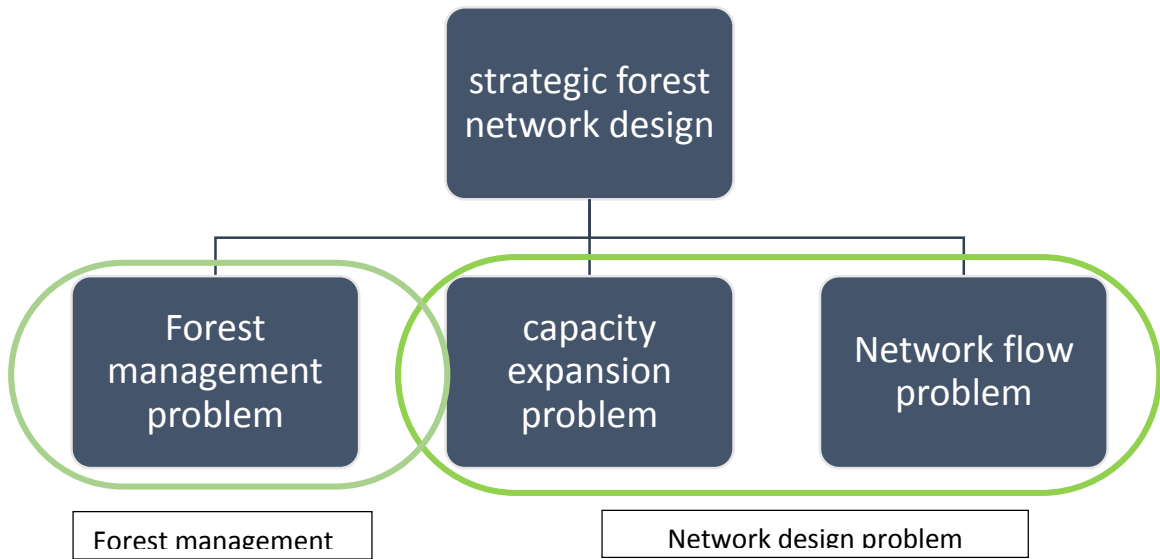


Figure 2 : Integrated network forest network design problem

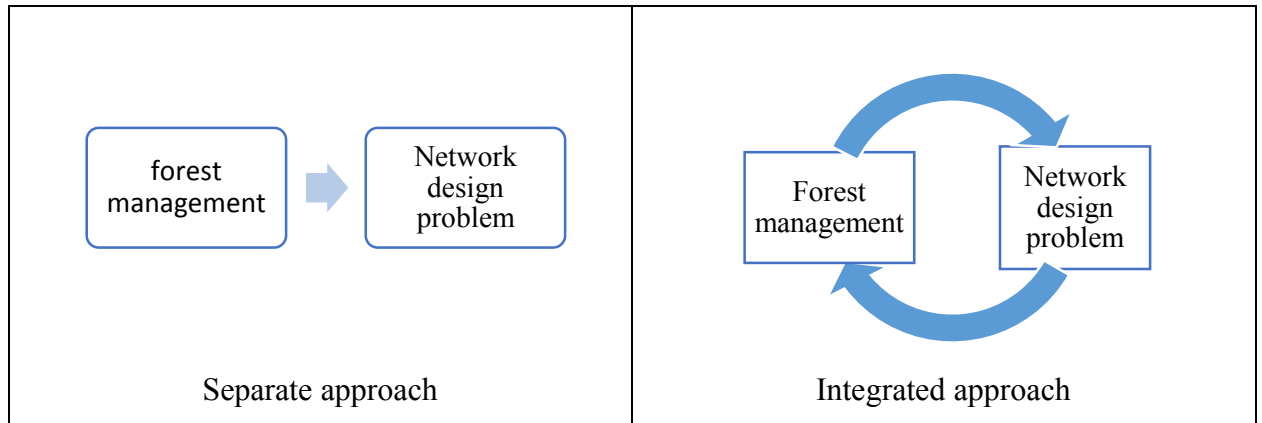


Figure 3 : Two different approaches toward forest management and network design problem

The questions we want to examine include the dependence of network design on the forest product outputs that result from the forest management process, the joint dependence of one type of capacity on other types of capacity and the change in the network designs with respect to final prices for various types of output. More specifically the research questions are:

1. Does consideration of network design including industrial capacity and location change forest resource management?
2. Does consideration of forest resource availability over time change network design, mostly capacity decisions?
3. Do integrated viewpoints lead to different joint strategies?

To answer these questions, and fulfill the research objectives, the problem will be formulated as mathematical models. The results of the mathematical models are used to compare the two approaches and discuss their differences in different characteristics of the network, from forest management to material flow and installed capacity. A simulation environment is used to generate sample forests and the mathematical models of joint forest management and capacity network design are applied to these forests. Although the forests we study are only simulated forests, they provide a capability for analysis regarding the dependence of different decisions in forestry. The result of this research can give valuable insight to have an efficient strategic decision making in forestry.

This thesis is organized into five chapters. The second chapter provides a review on the existing literature. Chapter 3 provides a more specific description of the problem and the related mathematical models. In the first section of this chapter, the forestry network will be explained in more detail. Mathematical models will be proposed for both the separate approach and the integrated approach in a deterministic environment. In the separate approach, the classical forest management model is used in the first phase and the result of the model will be used as the wood flow in the network design model. In the integrated model, both forest management and capacity decision are included in the same model. In chapter 4, the results are reported of numerical experiments conducted to answer the research questions. In the first section of this chapter, the data used to test the models are introduced. The simulation framework which is used to generate different forests, and the methods to generate different parameters for the mills and the flow of materials are explained in detail. Using this laboratory data set, the model's solutions are discussed in the next section. The discussion includes the comparison between the objective function and different costs in the system, the harvesting pattern, installed capacity and their locations in two approaches. The models are tested with different randomly generated sets of forests. The last analysis in this chapter is to make a comparison between the two approaches in different pricing scenarios. The final chapter provides conclusions and discusses possible future research.



## Chapter 2: Background

### 2.1. Introduction

The main objective of this research is to investigate decision making approaches for strategic forest value chain design. Forest value chain design encompasses many different issues including forest management, capacity expansion, and the supply chain network design problem. The first section of this chapter is a brief review of strategic planning in supply chain management and forestry. In the next section, strategic forest management and related mathematical models are studied. The third section is about capacity expansion, the economies of scale and location issues. In the last section, some past research on strategic network design in forestry is studied, and differences with current work are investigated. At the end of this chapter, the contribution of this research in terms of mathematical modelling is explained.

## 2.2. Supply chain Management Decision making and Strategic planning

A supply chain consists of a network of different suppliers, facilities, distribution centers, and customers. This network performs the function of material procurement, material transformation into intermediate and finished products and the distribution of the finished products to customers [3]. Design and management of such networks is a major challenge faced by decision makers.

More generally, in a supply chain network, many products and customers will be managed in parallel. As a result, instead of flows in a single chain, there are divergent and convergent flows in a complex network. Designing and managing the supply chain is the act of increasing competitiveness through such a network. In this concept, each of the organizations is not only responsible for their own profit and competitiveness, but as components of the network, they are also responsible for competitiveness of the whole chain. Although it may be impossible to increase all organizations' profit in the short term, to convince all organizations in the chain to participate in the whole chain's competitiveness, long-term advantages should be guaranteed. There are two basic means for improving the overall profit of the supply chain. The first is the integration of the organizations in the chain and the second is the better coordination of flows [4]. In the integration process, the goal is to overcome the companies' boundaries, which results in more cooperation between different organizations, from suppliers to customers. The coordination process tries to coordinate different types of flows including material, information, and financial flows. This thesis mostly focuses on the integration process.

There are three levels of decision making in supply chain management. These levels are strategic planning (long-term), tactical planning (medium-term), and operational planning (short term). The scope of this study is within strategic planning. Besides these levels, Shah [5] names three different problems in supply chain management, including: "1) supply chain network design, 2) supply chain analysis and policy formulation and 3) supply chain planning and scheduling". The first two problems, called "offline" activities, are about managing the supply chain network, and the third one is about how this network should operate [5]. This thesis focuses on supply chain network design.

In the previous paragraphs, decision making and strategic planning were discussed more generally. In the context of forestry, we follow the supply chain management concepts described above, but as we move forward, we need to be more focused on the supply chain in forestry. Carlsson et al. [6] showed the significant planning problems that may arise in a supply chain based on the pulp and paper industry. As the scope of this thesis is on forest management and capacity investment as long-term decision making, only the strategic planning part is presented (*Figure 4*).

	Procurement	Production	Distribution	Sales
<b>Strategic</b>	<ul style="list-style-type: none"> <li>• Wood procurement strategy (private vs public land)</li> <li>• Forest land acquisitions and harvesting contracts</li> <li>• Silvicultural regime and regeneration strategies</li> <li>• Harvesting and transportation technology and capacity investment</li> <li>• Transportation strategy and investment (e.g. roads construction, trucks, wagons, terminal, vessels, etc.)</li> </ul>	<ul style="list-style-type: none"> <li>• Location decisions</li> <li>• Outsourcing decisions</li> <li>• Technology and capacity investments</li> <li>• Product family allocation to facilities</li> <li>• Order penetration point strategy</li> <li>• Investment in information technology and planning systems (e.g. advance planning and scheduling)</li> </ul>	<ul style="list-style-type: none"> <li>• Warehouse location</li> <li>• Allocation of markets/customers to warehouse</li> <li>• Investment in logistics resources (e.g. warehouse, handling technologies, vessels)</li> <li>• Contracts with logistics providers</li> <li>• Investment in information technology and planning systems (e.g. warehouse execution)</li> </ul>	<ul style="list-style-type: none"> <li>• Selection of markets (e.g. location, segment) – customer segmentation</li> <li>• Product-solution portfolio</li> <li>• Pricing strategy</li> <li>• Services strategy</li> <li>• Contracts</li> <li>• Investment in information technology and planning systems (e.g. On-line tracking system, CRM)</li> </ul>

Figure 4: Problems at the strategic level of pulp and paper supply chains (Carlsson et al. [6])

Tasks in the supply chain can be classified into four different stages moving from suppliers' side to customers' side. These tasks are procurement, production, distribution and sales [4]. Capacity investment decisions are made in the procurement and production parts, but the factors that affect it and the factors on which the capacity decisions have effect, are not in the same block (*Figure 4*). For example, it is not useful to increase the capacity arbitrarily without considering the potential markets for the products. Another example in forestry is that the harvesting plan and the combination of species in the forest may have effect on the plants' type, location, and size.

D'Amours et al. [2], in a review paper on the application of operation research in forestry supply chains, implied that although operations research has been used for problems in this field extensively, an integration of different problems is still a challenge. These integrations are very complex, as the forest supply network consists of many-to-many processes.

There are many decisions that can be made at the strategic level, including forest management, road construction, opening and closing mills, product and market

development, and warehouse location and allocation. At this level, choosing different policies will affect decision making. For example, the type of forest land (public or private) or government policy will affect how the plants procure their supply from the forest. D'Amours et al. [2] implies that there is little research in the literature that considers the whole strategic problem from forest management to downstream supply chain decision making.

Carlsson and Rönnqvist [7], in their planning hierarchy, define procurement procedures in one module and production, distribution, and sales in another module in the strategic level. They stated that in strategic planning, harvest scheduling is defined by the government and will be used as an input for strategic wood supply planning. One of the objectives of this research is to study integrated forest management and investment decisions to investigate this gap in the literature and applications. In the next section, forest management and capacity expansion will be discussed separately.

### 2.3. Forest management

Though they should not be used in place of decision makers, strategic forest management models can provide additional support for decision makers in assessing forest strategies [8]. Many different factors in different disciplines need to be considered for efficient decision making in forestry. These can be classified into economic, environmental and social factors. For example, maximizing the harvested wood is an economic issue, optimizing wildlife habitat is an environmental issue, and creating jobs can be named as a social issue in this field. To deal with this interdisciplinary topic, many multi-criteria decision making (MCDM) methods from fuzzy logic to optimization and simulation have been used to help decision makers in the field [9-12]. However, all of these review papers focus on the forest in isolation. They do not mention the effect of forest management on other downstream parts of the forest industry supply chain or the effect of capacity expansion strategies on forest management.

The focus in this thesis is on strategic forest management models. These models assist the decision makers in assessing their strategies in forestry[8]. In order to do this

assessment, we may need to develop models which calculate how to harvest forests over a long time in a sustainable and profitable way.

Using mathematical models, we will discuss the modeling approach for forest harvest management. Three modeling approaches have been illustrated for long-term planning forest management [13, 14] (Figure 5).

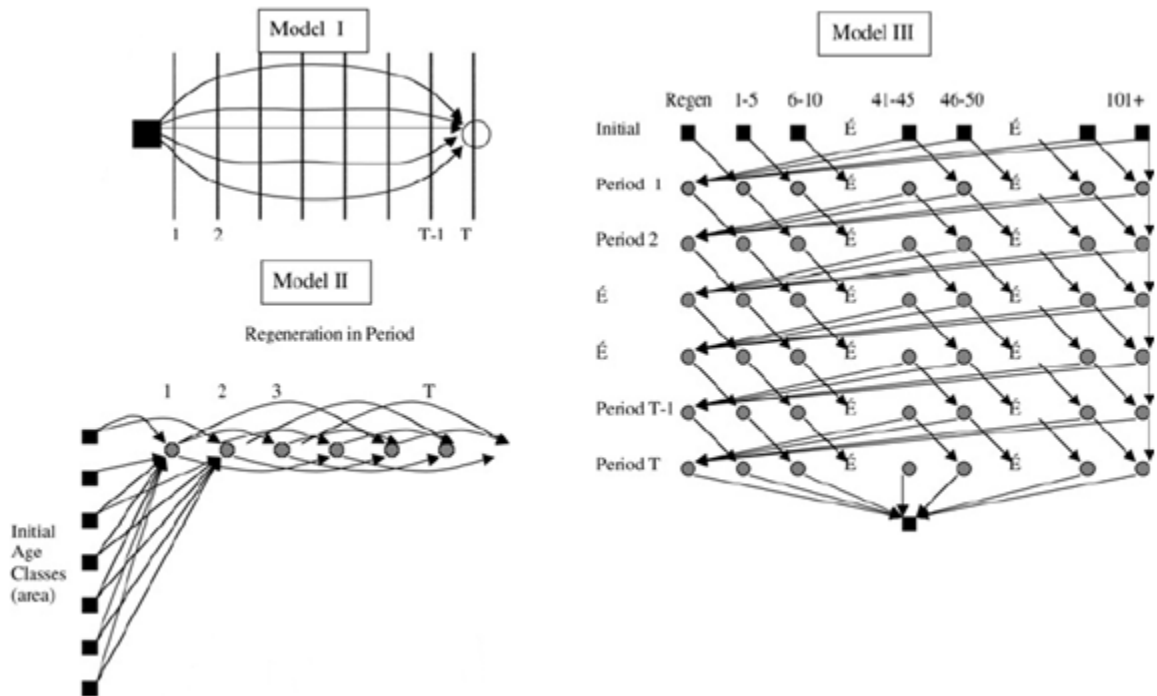


Figure 5: Different approaches for forest management, Gunn [13]

In Model I, different prescriptions are assigned to different stands and the stands keep their identities throughout the planning periods 1, 2, ..., T. A prescription is a set of scheduled forest interventions which are defined by the type and time of the intervention. For example, a set of clear-cut interventions at years 5, 55, and 105 is a prescription. In the next model, Model II, the stands will combine with each other based on their harvesting time. The arc  $(i,j)$  corresponds to an area regenerated in period  $i$  and harvested in period  $j$ . The aggregation in Model II implicitly allows more prescriptions to be considered. In Model III in each period, the land with the same age class may or may not be harvested. In the next period, it will revert to either regeneration or one class of age older. The structure

of the third model, in which the lands (aggregated stands with the same age class) keep their identities, make it ideal for modeling disturbance in forests, such as fire [15].

In Model I, stands can be aggregated or disaggregated, and each Model I arc can be shown as a path through equivalent nodes in the two other models [13]. Martin [16] in his thesis made a comparison between Models I and II and showed that although Model II has the ability to consider more prescriptions, if the correct prescriptions are used, the two models have the same objective function values. In addition, Model I is solved substantially faster than Model II, as the size of the problem increases.

Using Model I, in which the decision variables define how to assign prescription to different stands, it is possible to consider different issues whether in the objective function or constraints of the model. Maximizing the net present value, and minimizing the deviation from average cutting [17], maximizing harvest [18], and optimizing wildlife habitat[19] are some of the issues found in the objective function. In terms of constraints, minimum timber yield, even-flow constraint [18], adjacency rules [20], and non-declining-yields [16] are some of the issues considered. In this research, Model I will be used as the forest management model. While, in the integrated approach, the objective function is the net present profit of the system, in the separate approach the harvested wood volume is maximized in the forest management phase. Non-declining-yield is considered as the only constraint on forest management in both approaches.

Gunn [13] in 2009 proposed a mathematical model in which supply of raw material to different mills is also considered in strategic forest management modelling. The objective function of this model is to maximize the revenue from selling forest products to mills minus harvesting and transportation costs. The mathematical model in this thesis is an extension to this model, in which the capacity installation decisions are added to the model. Gunn [21] in 2014 presented an early version of this model in the context of a forest simulation. In this thesis, the revenue of the system is calculated based on the final product of each mill. To calculate the net profit, in addition to harvesting and transportation costs, landowner cost, capacity installation, fixed and variable operating costs are added to the model.

## 2.4. Capacity expansion and network design

Freidenfels [22] stated that "Economic progress and investments in capacity expansion go hand in hand". To keep an industry competitive, it is inevitable to decide about capacity expansion, and the forest industry is not an exception. As described in the introduction, capacity planning is one of the problems that needs to be determined in strategic network design. Three major decisions need to be considered in capacity expansion: expansion size, expansion time, and expansion location[23]. Julka et al. [24] illustrated the typical inputs and outputs in a capacity expansion process ( see *Figure 6*). When deciding about capacity expansion in forestry, many factors should be considered, including: expansion costs, current and future demand, and the interactions of mills with each other. Current and future forest availability and the combination of species are other factors which effect capacity expansion, and will be discussed in this research.

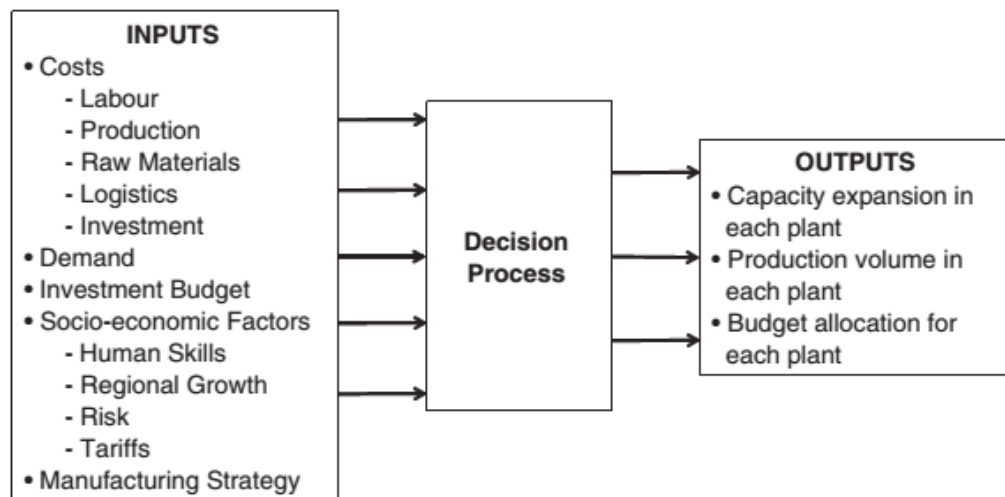


Figure 6 : Inputs and outputs for a typical capacity expansion process [24]

In many industries, when one increases the capacity or the scale of plants, the average unit cost of capacity will be reduced. This phenomenon, economies of scale, can justify having a few large plants instead of several smaller plants. Freidenfels[22] discusses two common cost functions in which the economies of scale are reflected. In the first, the cost of capacity expansion includes a fixed cost  $A$ , and variable cost per unit  $B$ . The total cost is equal to  $A+Bx$ , in which  $x$  is the amount of expansion. The second is  $kx^\alpha$ [22] in which

$k$  and  $\alpha$  are constants and  $x$  is the amount of capacity. Both of these two non-convex cost functions can be used as approximations for actual expansion costs.

In this thesis, the economies of scale are reflected in the capacity expansion cost and the operating cost of a plant. While the first cost function is used to approximate the operating cost of a plant, for capacity installation the second cost function is used. For the operating cost,  $A$  denotes the fixed cost and  $B$  denotes the variable cost per unit.

Although these cost functions are used to model the economies of scale, in terms of mathematical modelling, there is a drawback in their concave nonlinearity. There are different methods to deal with this problem. In the following paragraphs, some of these methods and the method which is used in this thesis are explained.

One method is to keep the model nonlinear and then use an efficient algorithm to solve it. Shen [25] proposed a supply chain design model with multiple products and economies of scale in the activity levels of the plants. In this problem, Shen [25] assumed that each facility cost exhibits economies of scale. The activity's cost has a concave function. As the author described, the cost function consists of three elements. If a facility is used to serve a customer, these three parts would be: the fixed location cost; a cost which is a linear function of the demand; and a cost which is a non-decreasing and concave function of fulfilled demand. To solve this problem, Shen kept the nonlinear cost function and used a Lagrangean relaxation method combined with a branch and bound algorithm [25]. Hsu and Li [26] develop a non-linear mixed integer programming model for a high technology supply chain network. Their paper concentrates on capacity planning considering economies of scale. Hsu and Li [26] solve the problem using a simulated annealing algorithm.

Another method is to use a piece-wise linear function approximation when  $kx^\alpha$  is used to reflect the economies of scale. Dasci and Verter [27] presented a model which considered plant location, capacity acquisition, and technology selection simultaneously in a multi-product environment. In this problem, there was a set of plant locations, a set of productions and a set of technologies. They assumed that the cost of purchasing and operating the technology is a monotone concave function of the capacity. Their objective function is to minimize the fixed cost of opening plants, cost of installation and using the



technology, and the transportation cost between plants and customers. To solve this problem, Dasci and Verter [27] used piece-wise linear approximation and a “pseudo-facility”, which refers to the linear segment of that function. The pseudo-facility in each segment has a capacity range, and in each range the operating costs are a linear function of the capacity.

The third method to deal with the nonlinearity of capacity expansion is to use discrete capacity expansions with their related costs. In this method, binary variables are used to select between different possible options [28], [29]. In this method, to cover more capacity options, more binary variables should be added to the model, while in the previous method the capacity sizes can be any point on the piece-wise linear function. Discrete capacity expansions method is more applicable as, in reality, the capacity expansion occurs in definite and discrete amounts. This discrete expansion model is used for capacity expansion decisions in this thesis, and will be explained in detail in Chapter 3.

When considering capacity expansion in a supply chain, it is not possible to ignore the logistics in the network. The suppliers provide raw material for the installed plants, and these plants provide final products for the customers, and raw material for other plants. Modifying the capacity of different elements in the supply chain, whether by decreasing or increasing it, will result in changes to material flow through the network, costs, and profits.

In some supply chains, with high investment cost and economies of scale, having centralized plants with larger capacity would be more cost beneficial in comparison with smaller decentralized plants, even if the former case will increase the transportation costs [26].

Where to locate a new facility or where the capacity expansion should take place is another issue which should be discussed. Facility location is a strategic decision, and it has a long-term effect on the supply chain. When the locations of new facilities are selected from a set of finite locations, we have a discrete facility location problem. In the simplest case, which is called the  $p$ -median problem, the challenge is to select  $p$  locations for  $p$  facilities among possible locations such that the total cost is minimized. When the fixed cost as a new parameter and the number of facilities as a new decision is added to the problem, it becomes more difficult to solve. In this case, if each facility has an infinite

capacity, the problem is called an uncapacitated facility location problem (UFLP). Otherwise it is called a capacitated facility location problem (CFLP)[30]. In this thesis, we are dealing with a CFLP, in which the capacity of the plant will be defined in the problem.

Elson [31] used a mixed integer program for a site location problem. In this problem he defines different binary variables for opening, closing, and expanding by the minimum amount. In this thesis, combining the capacity expansion and location decision, each binary variable has three indices corresponding to a type, location, and capacity expansion option. In the next section, capacity expansion and integrated network design in forestry will be explained in more detail.

## 2.5. Integrated network design in forestry

Forestry is an important process industry. Strategic supply chain planning and network design in different process industries have been studied extensively, which shows the importance of this concept in these industries. Although there are similar characteristics in these industries such as divergent flow of material, each of them has unique characteristics.

The petrochemical industry is one of the key industries in the world. What is much highlighted in this industry is uncertainty and risk regarding the price of crude oil and demand for petrochemicals [32],[33]. Although in forestry there are many risks and uncertainties in demand and prices of the products, the speed and variation are not comparable to the oil industry.

The mining industry is another important process industry in the world with more than 4% contribution to the world's GDP [34]. Defining long-term plans is one of the most crucial problems in this industry, because these plans provide a long term framework for lower level operations in mining [35]. Long term planning in this industry may deal with establishing policies from extraction to final products. One of the common strategic objectives is to maximize the return on investment over the planning horizon [8].

In comparison with other process industries, one of the characteristics, which is bold in forestry, is the dynamic nature of the forest as the initial source of raw material for the

network. The wood stands, the initial suppliers of the network, are spread over the land, and when they are harvested, they will be regenerated. How to manage this resource and the approaches to consider that as a part of an integrated network, will be investigated in this study. The current approach for integrated network design, is to manage the forest as a different decision making process which was explained in section 1.2. In the following paragraphs, some of the work on network design problems in forestry are investigated.

A forest network is a complex system, and considering all the elements from the forest to different types of capacity make the network design problem complicated. In many papers, only a specific type of mill or supply chain is considered, for example in the following works.

Troncoso and Garrido [28] considered a dynamic problem of integrated production and logistics in the forest industry and proposed a MIP model to solve this problem. They only considered timber supply chain and one kind of final product. The model solution defined the strategic selection of facilities' location and size, production level and freight flows in the planning horizon. The capacity of the plants may increase to a predefined level in the planning horizon. To define the plants' capacity they had different capacity options, and also different capacity expansion sizes, from which the model selects the best choice, depending on the total network cost, including production, transportation, investment, and fixed capacity expansion costs. The dynamic environment of the problem was reflected in the demand growth at a constant rate, without any uncertainties.

Vila et al. [36, 37] proposed a methodology for a production distribution network in the lumber industry. As their case study, they chose the Quebec lumber industry in which 90% of the forests are on public land. The lumber industry is highly influenced by the government as most harvesting and allocation decisions are made by the government. Strategic design of a supply chain involves all decisions in the company from forest operation and manufacturing to logistics and marketing departments. In this problem, the decisions about capacity, technology, manufacturing and marketing are made simultaneously [36].

Vila et al. [36, 37] defined different activities in the lumber industry and then these activities are mapped into potential layouts, capacities, and location options. Vila et al. [37]

in 2006 proposed an MIP model for this problem. The objective function is maximizing the net profit which is equal to all revenue including outflow to other sites and out flow to demand zone minus all expenses such as raw material, production, handling, and inflow.

The models that Vila et al. [36, 37] presented are within the forest management framework and use the decisions made at that level as inputs to their models. The effect of forest management on their models is mostly through the supply constraints which should be within the minimum and maximum limits that the government imposed. In other words, the models developed by Vila et al. [36, 37] mostly concentrate on the customers' side of the supply chain.

Another stream of papers focuses on utilizing forest biomass to produce energy and designing an efficient network for this purpose [38]. Shabani and Sowlati [39] presented a mixed integer non-linear programming model for value chain optimization at a tactical level. They focused on using the forest biomass to generate electricity and its possibility, depending on long-term availability, cost, and quality of biomass. The objective function is to maximize the overall value of the supply chain, which included the electricity selling revenue minus procurement, handling storage and production costs.

Camero et al. [40] propose a MIP model for supply chain optimization for forest residue to be utilized for energy and biofuel production. In this model, they define the type, the size, and the location of the facilities, the mix of their products from biofuel, and BioEnergy, the type, the amount, and source of BioEnergy they acquire from forest, and finally the amount of product which is sent to market. This work only focuses on the biofuel and BioEnergy supply chain.

The aforementioned papers in this section focused on specific types of products and supply chains with detail. The work in this thesis, considers the broader network, but with less level of details.

Feng et al. [29] presented a mathematical model for an integrated bio-refinery in a forest product supply chain. In addition to primary products flows, this model included the flow of energies, fuel, and biomass residues. This mathematical model found the optimal solution for investment decisions consisting of selecting facilities, their location, and

capacities. To consider economies of scale, the authors used an option for each facility with different sizes and technologies with binary variables used to decide if a facility with a certain technology and capacity option is selected. Feng et al.'s model [29] is an integrated, deterministic model, but it is not at the strategic level. The planning horizon for a solved problem is three years. Although it is possible to select between different suppliers including forests, the their capacities are known parameters in the model.

Gunn [41] presented a mathematical model for supply chain management in forestry. In this model, which is a multi-echelon, multi-period and multi-product problem, the objective function is to maximize the present value of revenue minus capacity expansion, operating, and transportation costs. As the author implies, the key feature of the model is the economies of scale in the capacity which take into account the trade-off between the number and the size of facilities and transportation costs. The estimation function which is used in this method is  $KX^\alpha$  in which  $K$  and  $\alpha$  are constant and  $\alpha$  is between 0.6 and 0.7 [41]. In this model the forest management is not considered in the capacity expansion model.

The studies discussed in this section are focused on a specific part of forestry, and do not consider forest management as part of the network design problem. In addition, as explained in section 1.2, in the forest management process the objectives and constraints are limited to the forest and the rest of the network is not considered in this decision making. In this study, to address this gap, we want to investigate whether the consideration of network design, including industrial capacity and location, change forest resource management. On the other hand, does consideration of forest resource availability over time change network flow and capacity decisions? This investigation, is done by comparing the separated and integrated decision making approaches, using MIP models and laboratory data. The idea and mathematical models proposed in this thesis, is a combination of the forest management [13] and capacity expansion models [41], proposed by Gunn, with some modifications.

## Chapter 3: Problem definition and mathematical modelling

### 3.1. Problem definition

The research problem is strategic integrated forest network design. In order to develop the strategic models being discussed in this thesis, it is useful to break the overall problem down into three main areas. The first is the problem of forest management which consists of which stands to harvest in each period to produce sustainable harvests. The second is the problem of which types of mill to build, where to build these mills and what size of mills to build in each location. The third is the logistics problem of managing the flow of the types of logs produced in the forest harvesting to the mills that can process those logs and the flow of intermediate products, such as chips and bark between the mills of various types. However, these problems are obviously not independent. Mill production must not exceed mill capacity. Log and intermediate inputs to the mill must correspond to the products produced and the intermediate outputs. Harvested logs transported to mills must correspond to the amounts of each log type harvested. Similarly, the amount of an

intermediate product transported from a mill to other mills must correspond to the amount of that intermediate product produced at that mill.

According to Gunn [42], “Strategic forest management models focus on the interaction between forest management decision, such as harvest and silviculture scheduling, and issues such as sustainability and economic returns from the forest”. In the mathematical models in this thesis, sustainability is reflected in the non-declining-yield constraint which guarantees that potential harvest volume in future periods will be at least the same as the current harvesting potential. There are other constraints that could be added to reflect special habitat management areas, ecodistrict cover and watershed cover requirements (see Martin [16]) but these non-declining yield constraints are all that we will use here.

The economic issues are reflected in the objective function of the mathematical models. If we consider the forest in isolation, this objective is reflected in the goals of maximizing harvested wood. This objective is restricted to forest products and it does not consider different value-added products in the downstream part of the supply chain. If the whole forestry network is considered, the objective function is the maximization of net present profit of the whole system.

In the network design problem, which consists of planning capacity and supply chain logistics, there are several issues such as types of mills, their interaction, their size, and their locations to be accounted for.

The capacities needed depend on the demand for and the price of products, and the available species in the forest. The appropriate capacities can be calculated based on the capital cost, operational cost, and customer demand. Economies of scale in investment costs result in fewer plants with larger sizes which may impose other costs on the system such as transportation costs. This trade-off between capital and operating cost is fundamental to any capacity planning problem, but the high cost of transporting green logs raises its importance in the types of problems considered here. The use of intermediate products produced at some types of mills as inputs for other types of mills, and the different cost characteristics of transportation of logs and intermediate products, mean that

transportation costs of logs and intermediate products have an important role in defining the mill locations and capacities.

As mentioned in chapter one, there are two general approaches for strategic forest network design, which are based on forest management and the design of the rest of the network. In the first approach, which is called “the separate approach” in this study, forest management is done as a separate process. Decisions about which stands to harvest and when to harvest them are defined in this phase and are reflected in the design of the forestry network as supply constraints. In a separate decision making process, capacity expansion and network logistic decisions can be made using forest management as a framework to define the log flow out of the forest.

The second approach, which is called “the integrated approach” in this study, considers forest management and designing the rest of the network in a single decision making process. In this approach, besides different constraints and considerations, forests are harvested based on the available and potential capacities and other network issues and the capacity expansion decisions, and network designs are made based on forest availability. In this approach, forest management and plant capacity expansion are viewed as interdependent parts. Instead of optimizing each of these sectors’ objectives individually, the overall objective is to maximize the whole system net profit.

As previously mentioned, the objective of this study is to investigate the separate approach, which is the current practice, and the integrated approach. This investigation is done using mathematical modelling and laboratory data. In the next section, the mixed integer mathematical programming models for the two approached are presented.

Before explaining the mathematical models, a general overview of the forestry network, which is studied here, will be presented. A more detailed explanation of the different elements of the network will be given in the data section in chapter 4.

The network that is studied in this research, consists of different elements (see Figure 1). These elements are forest stands, and different types of mills. These elements interact with each other through the flow of their products such as the flow of forest products to different mills, the flow of intermediate products from one mill to another, and the flow of



the final products from each mill. Although the mathematical model proposed in this chapter is quite general, and it is possible to consider different types of mills and products, only five mill types are considered in this thesis. These consist of softwood and hardwood sawmills, softwood and hardwood pulp mills, and BioEnergy plants.

The forestry network starts from the forest. The forest is divided into different stands which are pieces of land with the same characteristics, such as age, cover type, and site class, depending on the problem resolution. Each stand is located in a region. The centroid of the region is used to calculate the transportation cost to any destination, from any stands which are located in that region. These stands can be harvested using different prescriptions. These prescriptions, which are generated based on stand characteristics such as age, site class, and cover, will be explained in Chapter 4. Applying each of the possible prescriptions to a stand results in a specific amount of logs harvested in a specific time. This amount is called the yield.

There are different types of wood in the forest, based on different species. For example in this study two types of wood are considered: softwood and hardwood. This is an obvious simplification but similar to what other authors such as Paradis [43] have done. In addition to this classification, forest products have different types based on their potential usage. In this study, forest products are classified into different log types. Different types of logs will flow from the forest to different types of mills. Each type of mill can only accept specific types of logs. For example, a hardwood sawmill can accept hardwood sawlogs as an input but not hardwood pulp logs. Each mill can produce two kinds of product as output, final product and intermediate products. The intermediate products of one mill can be used as an input in other mills. A good example of an intermediate product is chips, which can be sent from sawmills to pulp mills or BioEnergy plants. Thus, a softwood pulpmill can receive softwood sawlogs, softwood pulp logs and softwood chips. Different multipliers are used to convert one unit of input products in one unit of operating level, and one unit of operating level to one unit of final products at each mill.

Given this network, the problem is how to harvest the forest over the long term. In addition, we have to determine the type, the size, and the location of different mills, as well

as how different products flow through this network. The two aforementioned decision making approaches have two different ways of answering these questions, which will be explained in the next section.

The objective adopted for the system in our modelling is to maximize the net present profit of the whole system which is equal to the revenue from selling final products minus the costs in the system. These costs include: harvesting costs, landowner costs, transportation costs, capacity expansion costs, and fixed and variable operating costs. There are other revenues and costs in the system, but they cancel each other when we look at the whole system. For example, a sawmill may sell its chips to a pulp mill. The sawmill gains revenue from selling the chips and the pulp mill increases its cost. These revenues and costs cancel each other, when we look at the whole system. In looking at maximizing net revenue for the entire system, we leave unresolved the problem of how to divide the revenues between the sawmill and pulp mill.

As mentioned in section 2.5, the idea and mathematical models proposed in this thesis, is a combination of the forest management [13] and capacity expansion models [41], proposed by Gunn. Gunn [21] proposed a mathematical model for this combination. This research extends this model with some modifications. For example, in Gunn's model [21], the revenue in the system is calculated based on the profit of selling logs to different mills. In this research, the final products are added to the system and the revenue is calculated based on final products price. Having final products in the system, results in some changes in the constraints as well. In addition, the landowner cost, fixed and variable operating costs are new in this model.

### 3.2. Mathematical modelling

In this section, the problems will be formulated as mathematical models for both separate and integrated approaches in a deterministic environment. In the separate approach, the classical forest management Model I will be used in the first phase and the result of the model will be fixed in the integrated network design model. In the integrated approach, the forest management is considered as part of network design decisions in one model. Before presenting the mathematical model, it is worthwhile to explain three

modelling issues about forest management and capacity decisions and list the modelling assumptions.

In the forest management model, stands, prescriptions, and periods are the main sets. A prescription is a set of clear-cut interventions during the planning horizon which is defined by the type and time of the intervention. For the purposes of this thesis, we deal with simple single-entry even-aged forest management (see Davis et al. [44]) but it is not difficult to also consider multiple entry or uneven aged prescriptions. Based on the growth rate and the appropriate time to harvest, an acceptable set of prescriptions will be generated and this set will be used as an input for the forest management model. How these prescriptions are generated will be explained in detail in chapter 4. The basic decision variable for this model,  $X_{ik}$ , is the area of each stand assigned to a prescription.

In the capacity decisions, the capacity expansion cost is a nonlinear function of capacity in which the economies of scale are reflected. In this thesis, the nonlinear cost function will not be used; first, because it makes the model nonlinear, it is harder to find an optimal or near optimal solution; second, in reality the expansion will occur in defined increments. Instead of using nonlinear cost functions and continuous decision variables in the models, binary variables are used to define a size for each plant type at each location. Using this method for each plant at each location there are different capacity options, and the mathematical model will only select one of these options. Building nothing is always an option.

There are two sets of periods in the model,  $T_1$  and  $T_2$ .  $T_1$  is less than  $T_2$ , and it is the set of periods in which the whole system including the mills and different flows are modeled. The planning horizon for strategic forest management is usually more than 100 years. Although both forest management and capacity expansion exist at the strategic level, it is not practical to decide on new types of facility installation over such a long time (for example more than 30 years). When to install new capacities depends on the available budget, demand trend, and the current capacities. In addition, to deal with the uncertain market environment and new emerging products in the future, it is more logical to decide new capacities for the near future when the anticipation about different costs, budgets, and

market situations is more reliable. In theory, it is possible to repeat  $T_2$  in  $T_1$  planning horizon, but as mentioned before it is not possible to provide reliable data for a far future.

Table 1: Sets

Set	Definition
$I$	Set of stands
$R$	Set of regions
$I(r)$	Set of stands belonging to region $r$
$T_1$	Planning periods for modelling the total network economics
$T_2$	Planning periods for forest management
$p(i)$	Set of possible prescriptions for stand $i$
$M$	Set of mill types
$F$	Set of final products
$F(m)$	Set of final products belonging to mill type $m$
$INT$	Set of intermediate products
$INT(m_1m_2)$	Set of intermediate product that can flow from mill type $m_1$ to mill type $m_2$
$L$	Set of locations
$W$	Set of wood (species) types
$L_g$	Set of log types
$L_g(m)$	Set of log types belonging to mill type $m$
$N(m)$	Set of capacity options belonging to capacity type $m$

In addition to the aforementioned modelling issues, the following assumptions were considered:

1. The capacities are installed at the beginning of the planning horizon.
2. If the capacity is established, beside the initial installation cost, there is also the fixed operating cost in each planning period.
3. For each type of mill, different input flows have their own contributions to the operating level, independent of other flows.
4. The market demand for the final products is not limited and if there is production in the system, it will be absorbed by the market.
5. It is possible to have multiple types of mills in one location.

The sets, parameters, and decision variables are presented in Table 1, Table 2 and Table 3, respectively.

Table 2: Parameters

Parameter	Definition
$HMult$	Harvested wood multiplier
$fMult$	Final revenue multiplier
$tMult$	Transportation cost multiplier
$hMult$	Harvesting cost multiplier
$lMult$	Land owner cost multiplier
$oMult$	Operating cost multiplier
$cMult$	Capacity cost multiplier
$\alpha Mult$	Alpha multiplier (Penalty for non-declining-yield constraint)
$FPrice_{fm}$	$m \in M, f \in F(m)$ Price of final product $f$ at mill type $m$
$HarvCst_w$	$w \in W$ Harvesting cost of wood type $w$
$ITrCst_{pl_1l_2}$	$p \in INT, l_1, l_2 \in L$ Transportation cost of intermediate product $p$ from location $l_1$ to location $l_2$
$LTrCst_{l_g r l}$	$l_g \in L_g, r \in R, l \in L$ Transportation cost of log type $l_g$ from location region $r$ to location $l$
$Capacity_{mn}$	$m \in M, n \in N(m)$ Capacity of mill type $m$ at $n^{th}$ option (nonlinear cost function changed to Piece-wise linear)
$CapCost_{mn}$	$m \in M, n \in N(m)$ Capital cost of opening capacity of type $m$ at $n^{th}$ option
$Area_i$	$i \in I$ The area of stand $i$
$Harv_{ikt w}$	$i \in I, k \in p(i), t \in T_2, w \in W$ The amount of harvest in stand $i$ using prescription $k$ from wood type $w$ at period $t$
$LHarv_{ikt l_g}$	$i \in I, k \in p(i), t \in T_2, l_g \in L_g$ The amount of harvest in stand $i$ using prescription $k$ from log type $l_g$ in period $t$
$YIP$	Number of years in each period
$multL_{l_g m}$	$m \in M, l_g \in L_g(m)$ Conversion multiplier for one unit of log $l_g$ as an input, to one unit of operating level at mill type $m$
$multI_{p m}$	$m \in M, p \in INT$ Conversion multiplier for intermediate product $p$ as an input, to one unit of operating level at mill type $m$
$multIO_{p m}$	$m \in M, p \in INT$ Amount of output intermediate product flow $p$ for one unit of operating level at mill type $m$
$multF_{f m}$	$m \in M, f \in F(m)$ Amount of output final product flow from one unit of operating level at mill type $m$
$dFact_t$	$t \in T_1$ Discounting factor at time $t$
$FixOp rt_m$	$m \in M$ Fix operating cost per year for each type of mill
$VarOp rt_m$	$m \in M$ variable operating cost for each type of mill

The multipliers  $fMult$ ,  $tMult$ ,  $hMult$ ,  $lMult$ ,  $oMult$ ,  $cMult$ ,  $\alpha Mult$  are provided to enable the decision maker to decide what costs to count in the objective. If the user does not want a certain term to contribute to the objective, they need to set the corresponding multiplier to zero.

Table 3: Decision Variables

Decision Variable		Definition
$FinalRev_t$	$t \in T_1$	Final products revenue at period t
$HarvCost_t$	$t \in T_1$	Harvesting cost at period t
$LandOwner_t$	$t \in T_1$	Land owner cost at period t
$TransCost_t$	$t \in T_1$	Transportation cost at period t
$TotAlpha$		Total alpha which shows the non-declining-yield constraint violation
$TotCapacityCost$		Total capacity expansion cost
$OprrtCost_t$	$t \in T_1$	Operating cost at period t
$FixOprrtCost_{tml}$	$t \in T_1, m \in M, l \in L$	Fix operating cost of mill type m at location l in period t
$VarOprrtCost_{tml}$	$t \in T_1, m \in M, l \in L$	Variable operating cost of mill type m at location l in period t
$Alpha_{tw}$	$t \in T_1, w \in W$	Alpha for wood type w in period t, which shows the non-declining-yield constraint violation for wood type w in period t
$LTrans_{tl_g r ml}$	$t \in T_1, m \in M, l \in L, r \in R, l_g \in L_g(m)$	Amount of log type $l_g$ sent from region r to mill type m at location l in period t
$ITrans_{tpm_1 l_1 m_2 l_2}$	$t \in T_1, m_1 \in M, l_1 \in L, m_2 \in M, l_2 \in L, p \in INT(m_1, m_2)$	Amount of intermediate product p sent from mill type $m_1$ at location $l_1$ to mill type $m_2$ at location $l_2$ in period t
$FTrans_{t f ml}$	$t \in T_1, m \in M, l \in L, f \in F(m)$	Amount of final product f produced in mill type m at location l
$ZCap_{mln}$	$m \in M, l \in L, n \in N$	Binary variable which is equal to 1 if for mill type m at location l section n is used
$Cap_{ml}$	$m \in M, l \in L$	New capacity installed for mill type m at location l
$X_{ik}$	$i \in I, k \in P(i)$	Acres of stand i which is harvested using prescription k
$OL_{tml}$	$t \in T_1, m \in M, l \in L$	Operating level at mill type m at location l in period t
$H_{tw}$	$t \in T_2, w \in W$	Amount of harvest from wood type w in period t
$regLH_{tl_g r}$	$t \in T_2, l_g \in L_g, r \in R$	Amount of harvest in region r from log type $l_g$ at period t

### 3.2.1. The mathematical model for the integrated approach

The mathematical model for the integrated approach is presented as follows. The same model will be used in the separate approach after fixing the forest management decision variables. This approach will be explained in the next section.

$$\text{Maximize Net Profit} \quad (1)$$

$$\begin{aligned} &= \sum_{t \in T_1} dFact_t \times (fMult \times FinalRev_t - hMult \times HarvCost_t - lMult \\ &\quad \times LandOwner_t - tMult \times TransCost_t - oMult \times OprtCost_t) - cMult \\ &\quad \times TotCapacityCost - aMult \times TotAlpha \end{aligned}$$

s.t.

$$FinalRev_t = \sum_{m \in M} \sum_{f \in F(m)} \sum_{l \in L} FPrice_{fm} \times FTrans_{t f m l} \quad t \in T_1 \quad (2)$$

$$HarvestCost_t = \sum_{w \in W} HarvCst_w \times H_{tw} \quad t \in T_1 \quad (3)$$

$$LandOwner_t = \sum_{l_g \in L_g} \sum_{r \in R} \sum_{m \in M} \sum_{l \in L} LandOwnerCst_{l_g} \times LTrans_{t l_g r m l} \quad t \in T_1 \quad (4)$$

$$\begin{aligned} TransCost_t &= \sum_{l_g \in L_g} \sum_{r \in R} \sum_{m \in M} \sum_{l \in L} LTrCst_{l_g r l} \times LTrans_{t l_g r m l} \\ &+ \sum_{m_1 \in M} \sum_{l_1} \sum_{m_2 \in M \setminus \{m_1\}} \sum_{l_2} \sum_{p \in INT(m_1 m_2)} ITrCst_{i l_1 l_2} \times ITrans_{t p m_1 l_1 m_2 l_2} \end{aligned} \quad t \in T_1 \quad (5)$$

$$OprtCost_t = \sum_{m \in M} \sum_{l \in L} FixOprtCost_{t m l} + \sum_{m \in M} \sum_{l \in L} VarOprtCost_{t m l} \quad t \in T_1 \quad (6)$$

$$FixOprtCost_{t m l} = \sum_{n \in N(m)} FixOprt_m \times ZCap_{m l n} * YIP \quad t \in T_1, m \in M, l \in L \quad (7)$$

$$VarOprtCost_{t m l} = VarOprt_m \times OL_{t m l} \quad t \in T_1, m \in M, l \in L \quad (8)$$

$$TotCapacityCost = \sum_{m \in M} \sum_{l \in L} \sum_{n \in N(m)} CapCost_{m n} \times ZCap_{m l n} \quad (9)$$

$$TotAlpha = \sum_{t \in T_2} \sum_{w \in W} Alpha_{t w} \quad (10)$$

$$\sum_{k \in P(i)} X_{ik} = Area_i \quad i \in I \quad (11)$$

$$H_{tw} = \sum_{i \in I} \sum_{k \in p(i)} Harv_{ikt w} \times X_{ik} \quad t \in T_2, w \in W \quad (12)$$

$$H_{tw} \leq H_{t+1w} + Alpha_{tw} \quad t \in T_2, w \in W \quad (13)$$

$$regLH_{tlgr} = \sum_{i \in I(r)} \sum_{k \in p(i)} LHarv_{ikt l_g} \times X_{ik} \quad t \in T_1, l_g \in L_g, r \in R \quad (14)$$

$$regLH_{tlgr} = \sum_{m \in M} \sum_{l \in L} LTrans_{tlgrml} \quad t \in T_1, l_g \in L_g, r \in R \quad (15)$$

$$OL_{tml} = \sum_{r \in R} \sum_{l_g \in L_g(m)} multL_{l_g m} \times LTrans_{tlgrml} \\ + \sum_{m_1} \sum_{l_1} \sum_{p \in INT(m_1, m)} multI_{p m} \times ITrans_{tpm_1 l_1 ml} \quad t \in T_1, m \in M, l \in L \quad (16)$$

$$FTrans_{t f ml} = OL_{tml} \times multF_{f m} \quad t \in T_1, m \in M, f \in F(m), \\ l \in L \quad (17)$$

$$\sum_{m_1 \in M} \sum_{l_1 \in L} ITrans_{tpm_1 l_1 ml} = \sum_{r \in R} \sum_{l_g \in L_g} LTrans_{tlgrml} \times multIO_{p m} \\ t \in T_1, m \in M, \\ l \in L, p \in INT(m, m_1) \quad (18)$$

$$OL_{tml} \leq YIP \times Cap_{ml} \quad t \in T_1, m \in M, l \in L \quad (19)$$

$$Cap_{ml} = \sum_{n \in N(m)} ZCap_{mln} \times Capacity_{mn} \quad m \in M, l \in L \quad (20)$$

$$\sum_{n \in N(m)} ZCap_{mln} \leq 1 \quad m \in M, l \in L \quad (21)$$

The objective function is net present profit in the system (1) which is equal to the present value of final revenue minus harvesting costs, the transportation costs, operating costs and capacity expansion costs. The last element in the objective function is used to control the non-declining yield. As mentioned above, each of the elements in the objective function has a multiplier which can be used as a weight. In this thesis, there is no difference between the revenue and different costs in terms of weight. Parameter  $\alpha Mult$  is used to penalize the objective function to ensure that the non-declining-yield constraint is satisfied.



Equation (2) calculates the final revenue of the system. The final revenue is calculated based on the amount of final products produced at each mill and their unit price. Equation (3) calculates the harvesting cost which is equal to the amount of harvest multiplied by the harvesting cost per cubic meter of wood. In reality, the harvesting cost is calculated per ton, and we assume that one ton of wood is approximately equal to one cubic meter. The landowners should have a fixed amount of profit per unit for each type of log they sell. This cost can also be interpreted as the stumpage value. Equation (4) calculates the landowner cost, which is equal to the amount of log harvested multiplied by the landowner cost per cubic meter for each log type.

Equation (5) shows the transportation cost which is equal to the log transportation cost from forest to mills and the intermediate product transportation cost from one mill to another. Equation (6) shows that the operating cost is equal to the fixed operating cost plus the variable operating cost. There is a fixed operating cost in each planning period if the mill is working. This cost is calculated by equation (7). The variable operating cost is calculated based on the operating level of each mill in each planning period (8).

Capacity installation cost is calculated by equation (9), based on the capacity option, which is equal to the binary decision variable related to a specific point on the installation cost function and the cost pertaining to that.

Total alpha is equal to the sum of all alpha for each type of wood and in each planning period (10). This is the sum of all violations of the non-declining yield constraints, which is then penalized in the objective function.

Constraint (11) guarantees that the sum of acres of land in a stand which are harvested using different prescriptions is equal to the total area of the stand. Constraint (12) calculates the amount of wood which is harvested in each planning period from each type of wood. Constraint (13) is the non-declining-yield constraint, which guarantees that potential harvest volume in future periods, will be at least the same as the current harvesting potential. Constraint (14) calculates the amount of log which is harvested from each log type in each region and in each planning period.

Constraint (15) shows the out-flow from each region for each log type in each planning period. The in-flow in (14) and the out-flow in (15) are equal to each other using variable  $regLH_{tigr}$ . Constraint (16) shows the operating level of each mill, which is

calculated based on the input flow. The input flow to each mill includes the log flow and intermediate product flow. Constraint (17) shows the final product production which is calculated based on the operating level of each mill. Constraint (18) shows the intermediate products production which is based on input wood flow to each mill. In this constraint, the amount of intermediate product, which is sent in each planning period from each mill in each location, is equal to the amount of wood processed in that mill multiplied by its yield.

Constraint (19) shows the capacity limit for each mill. The capacity of the mill is per year while the operating level is over each planning period. To solve this inconsistency, the capacity is multiplied by the number of years in each planning period. Constraints (20) and (21) define the capacity of each installed mill. For each mill at each location, only one expansion option is selected (21).

### 3.2.2. The mathematical model for the separate approach

The separate approach consists of two phases. In the first phase, the mathematical model for forest management is solved. In the second phase, based on the result of this model, the  $X_{ij}$  decision variables are fixed and then the mathematical model for the integrated approach will be run to define the other decision variables in the system. In other words,  $X_{ik}$  decision variables in the integrated model are parameters in the second phase of the separate approach, in the same mathematical model. The value of  $X_{ik}$  variables are defined in the first phase, using the forest management model.

The mathematical model for forest management in the separate approach is as follows:

$$\text{Maximize Total Volume} = \sum_{t \in T_2} \sum_{w \in W} HMult \times H_{tw} - \alpha Mult \times TotAlpha \quad (22)$$

s.t.:

$$TotAlpha = \sum_{t \in T_2} \sum_{w \in W} Alpha_{tw} \quad (23)$$

$$\sum_{k \in p(i)} X_{ik} = Area_i \quad i \in I \quad (24)$$

$$H_{tw} = \sum_{i \in I} \sum_{k \in p(i)} Harv_{ikt} \times X_{ik} \quad t \in T_2, w \in W \quad (25)$$

$$H_{tw} \leq H_{t+1w} + Alpha_{tw} \quad t \in T_2, w \in W \quad (26)$$

The objective function (22) is the maximization of the harvested wood volume. The second section in the objective function is to control the non-declining-yield constraint. The amount of harvested wood is the result of applying prescription  $k$  to stand  $i$ . Constraints (23) to (26) are explained in the integrated model. The outcome of this model will define the flow of raw material from forest to other downstream elements of the supply chain.

After this model is solved, the  $X_{ik}$  decision variables will be fixed in the integrated model and then it is solved. In other words, in this model the available resource is a parameter which is calculated in the forest management model. In the integrated approach it would be a decision variable which will be defined in the model with other decision variables such as capacity variables. It is worthwhile to explain that to solve both separate and integrated approaches, there is one mathematical model in the system. Different elements of the objective function are controlled by their multipliers. For example to solve the forest management model in the first phase of the separate approach, all the multipliers except the  $HMult$ , and  $\alpha Mult$  are equal to zero. After solving this model and fixing  $X_{ik}$  variables,  $HMult$  and  $\alpha Mult$  are set to zero and all other multipliers are set to 1. For the integrated approach  $HMult$  is set to 0.

The models explained in this chapter are general models which are not limited to specific types of mills and forestry networks. In the next chapter, the models will be tested using some sample problems with 15 regions, 3000 stands, and 6 different types of mill.

## Chapter 4: Computational Experiment and Results

### 4.1. Introduction

This chapter describes numerical experiments used to investigate the proposed approaches, and to test and analyze the mathematical models. This chapter is organized into two sections. In the first section, the simulation data which is used to test the models is explained. In the next section, using these data sets, the solution of the mathematical models will be analyzed.

### 4.2. Simulations for generating research data

In this section, the data, which is used to investigate the integrated and separate approaches, is explained. In section 4.2.1, a simulation framework which is used to create forest scenarios, is presented. In section 4.2.2, data for different types of mills, including possible inputs and outputs, installation cost, fixed and variable operating costs, and possible locations are introduced. In section 4.2.3, the parameters needed to calculate different types of flows in the system are presented.

#### 4.2.1. Forest data

The forest data is generated by a simulation model. The modelled forests have many stands, each located in a specific region. Each stand has different characteristics: i) area, ii) cover type (softwood, mixedwood, and hardwood), iii) initial age, iv) site class (measure for growth ability) , v) stocking (stand density) , and vi) regional location. Each characteristic for each stand is generated based on some given probability distribution using an Excel spreadsheet. A snapshot of the excel file is presented in Appendix A. These data will be used either directly as the parameters of the model such as stand area, or indirectly to generate prescriptions and yield parameters.

Table 4 shows a sample of 10 stands and their area. This data, and that used in the rest of the work reported in this thesis, was generated randomly using an exponential distribution with 3000 stands, each with an expected value of 1000 acres.

Table 4: 10 different stands and their areas

<b>Stand</b>	<b>Area</b>	<b>Stand</b>	<b>Area</b>
<b>1</b>	348.78	6	255.22
<b>2</b>	628.43	7	4267.43
<b>3</b>	545.55	8	273.48
<b>4</b>	1239.38	9	205.19
<b>5</b>	1197.50	10	343.84

Stands have a location used to calculate transportation distances and costs. The total forest area is broken down into many regions and each stand is located in one region with a given probability. The central point of each region is used to approximate the distance between stands in that region and the mills and to calculate the transportation cost. In this thesis, stands are distributed over 15 different regions. Coordinates of the different regions, and their related probability are presented in Table 5. Each region has a different percentage of the total area.

Each of the stands has its own characteristics which will be used to generate prescriptions. Table 6 shows these characteristics, which are initial age, site class, cover and stocking. Figure 7 shows histograms of these characteristics based on their probability that we have used for this thesis. There are three cover types: “Softwood”, “Mixed wood”, and

“Hardwood”. Although we could have simulated softwood percentages directly, we assume that “Softwood”, “Mixed wood”, and “Hardwood” have 95%, 65%, and 25% of softwood, respectively.

Table 5: Regions and their coordinates

Region	RegX	RegY	Probability (%)	Region location																			
1	25	25	6	<table border="1"> <tr> <td>3</td> <td>4</td> <td>9</td> <td>10</td> <td>13</td> </tr> <tr> <td>2</td> <td>5</td> <td>8</td> <td>11</td> <td>14</td> </tr> <tr> <td>1</td> <td>6</td> <td>7</td> <td>12</td> <td>15</td> </tr> </table>					3	4	9	10	13	2	5	8	11	14	1	6	7	12	15
3	4	9	10						13														
2	5	8	11						14														
1	6	7	12						15														
2	25	75	8																				
3	25	125	6																				
4	75	125	6																				
5	75	75	5																				
6	75	25	7																				
7	125	25	7																				
8	125	75	7																				
9	125	125	6																				
10	175	125	7																				
11	175	75	7																				
12	175	25	6																				
13	225	25	6																				
14	225	75	7																				
15	225	125	8																				

Table 6: Stand characteristics for generating prescriptions

Age	Probability (%)	Site	Probability (%)	Cover	Probability (%)	Stock	Probability (%)
0	5	3	10	Softwood	60	30	15
20	20	4	30	Mixed wood	20	40	20
40	20	5	30	Hardwood	20	50	30
60	25	6	20			60	20
80	20	7	10			70	10
100	5					80	5
120	5						

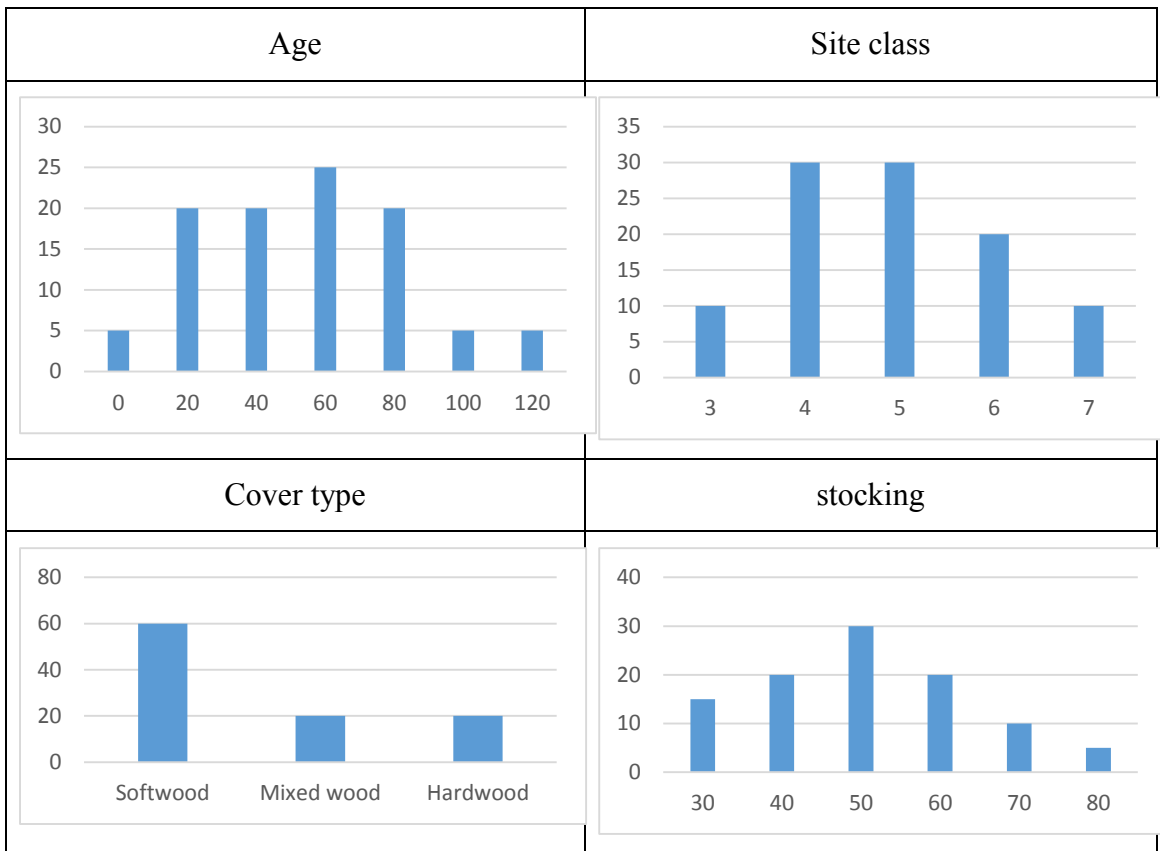


Figure 7: Histograms of stand characteristics

Based on its site class, each stand has different growth rate. *Figure 8* shows the actual growth rate diagram for different site classes. For the current data set, the growth rate diagrams for each site class are approximated using three points from the actual diagrams (*Figure 9*). These three points are year 0, the year in which the rate is maximum, and year 100. For example, for site class 7, year 0, year 55, and year 100 are considered. The Growth rates at these years are equal to 0, 7.2, and 6. Based on these three points the growth rate of other points are calculated linearly.

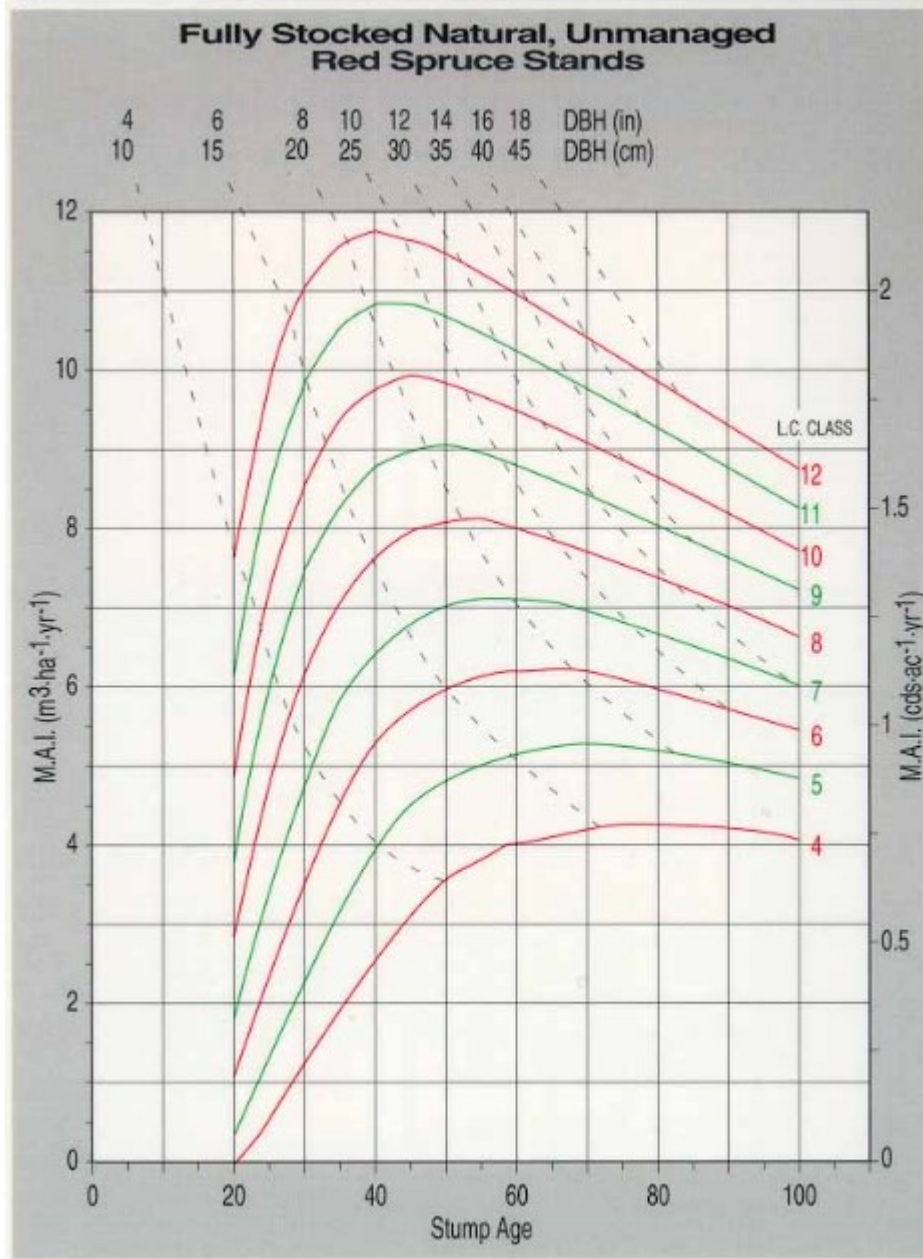


Figure 8: Growth projection diagram based on different site classes [13]



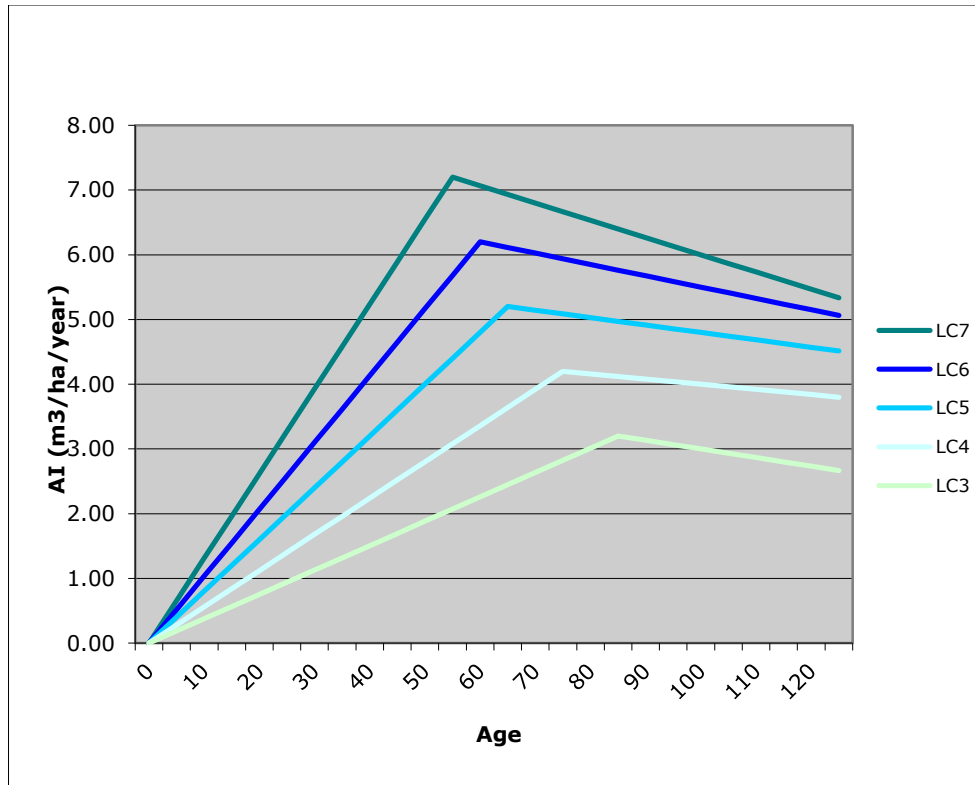


Figure 9: Approximated annual Increment as a Function of Age and Site [13]

Based on the growth projection diagrams, an optimum harvesting age can be taken as that at which the growth rate is maximized in that stand, the age of maximum mean annual increment (MAI). Having this optimum time, three types of harvesting age are generated: early, on-time, and late harvest. Early time is approximately 10% less and late time is approximately 10% more than on-time age. The actual early, on-time and late ages are shown for each land capability in Table 7 along with corresponding full stocking harvest volumes [13].

Table 7: Early, on time, and late age years and their full stocking

Site class		3	4	5	6	7
age ontime	Year	85	75	65	60	55
	Full stocking	272	315	338	372	396
age early	Year	75	65	55	55	50
	Full stocking	211.76	236.6	242	312.58	327.27
age late	Year	90	80	70	70	65
	Full stocking	282	332.8	360	421.75	450.67

Feasible combinations of these timings plus no harvest will make a set of prescriptions. These prescriptions are even-aged prescriptions. If E stands for early, O for on time, L for late and N for no harvest, the possible set of prescriptions which are considered here are: 'EEE', 'EEO', 'EEN', 'EON', 'ELN', 'ENN', 'OEE', 'OEO', 'OEN', 'OON', 'OLN', 'ONN', 'LEE', 'LEN', 'LON', 'LLN', 'LNN', 'NNN'.

Based on the stand's initial age and site class, which define the harvesting times of the aforementioned prescriptions, and the planning horizon as the constraint, a set of feasible prescriptions for each of the stands is generated. For example, if a stand is 50 years and its site class is 5, the prescriptions EEN, EON, ENN, OEN, OON, OLN, ONN, LEN, LON, LLN, LNN, NNN are feasible prescriptions. This is because the last harvesting period of these prescriptions are within the planning horizon, which is 105 years or 21 periods. For example, the harvesting years for prescription EEN for the same stand is year 5 and year 60. This is because the early age for this stand is 55, and the initial age is 50. The first harvest will occur 5 years from now, and the second harvest will occur starting 60 years from now. In terms of periods, the harvesting periods will be 2 and 13.

The result of applying each prescription on a stand, is reflected as the amount of wood and different forest products which come out of the forests at the harvesting periods. This information is stored in the yield table (*Table 10*) as one of the parameters of the models. Before explaining how to create the yield table, it is necessary to introduce different wood types and forest products in this study.

There are different types of wood in forests. In the current sample data, there are two types of wood: softwood and hardwood. In reality, the wood can be classified into more detailed types. In addition to wood types which are used in the forest management models, forest products are classified into more types based on their usage. In the current sample data, there are six types of log as the forest products (*Table 8*).

Table 8: Log Types

ITypes	Name	Description
1	sPlpLog	Softwood pulp log
2	sStudLog	Softwood stud log
3	sLog	Softwood saw log
4	hPlpLog	Hardwood pulp log
5	hStudLog	Hardwood stud log
6	hLog	Hardwood saw log

For each entry in the yield table, the combination of stand, possible prescription, and period is unique. The first three columns are stand number, prescription number, and period number. As the planning period in this study is equal to 5 years, the harvesting time for each prescription is divided by 5 to define the period number. The other columns are the amount of harvest per acre for softwood, hardwood, softwood pulp, softwood stud, softwood log, hardwood pulp, hardwood stud, and hardwood log in cubic meter from the specific stand, using the specific prescription, in the specific period.

Multiplication of harvesting age and the annual increment at that age results in full stocking volume as a function of age for each stand (Figure 10). To calculate the cubic meters per acre of wood in each stand, full stocking volume at that age is multiplied by stocking of that stand.

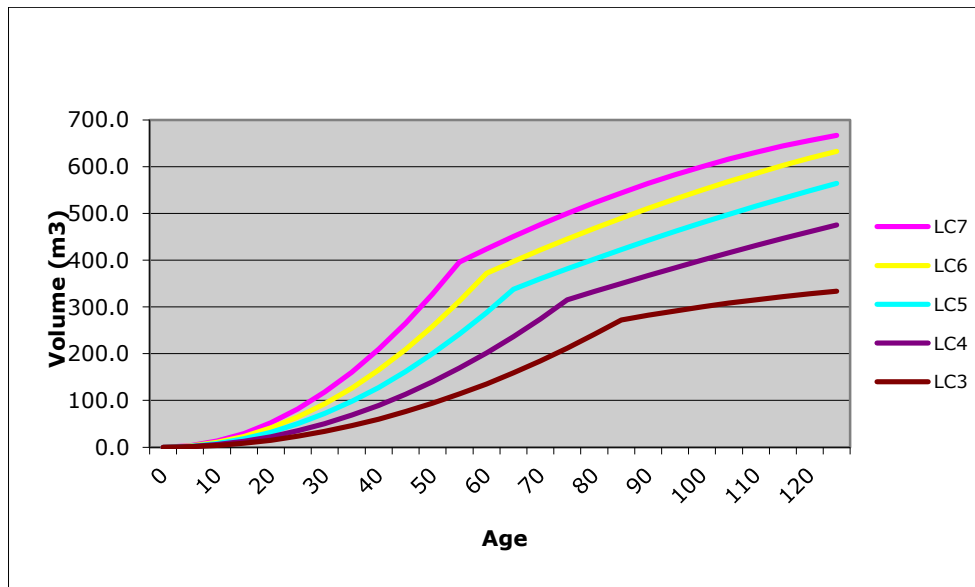


Figure 10: Full stocking volume as a function of age and site [13]

To disaggregate this number for softwood and hardwood, and other log products, different formulas are used, which are derived from Nova Scotia fully stocked normal yield table with some modifications [45]. These numbers are presented in different columns of the yield table. Each of these numbers and the formulas which have been used to calculate them are displayed in Table 9. In addition to previous stand characteristics, the cover type of the stand should be taken into account. For example if a stand cover is softwood, the wood volume is multiplied by 0.95, to calculate the cubic meter per acre of softwood out of the forest. This number for hardwood volume in the same stand is calculated by multiplying the wood volume by  $(1-0.95) \times 0.6$ . This is because a softwood stand consists of 95% softwood and 5% hardwood, and the volume growth rate of hardwood is about 60% of softwood growth rate.

The pctLogs and studLogs are based on a linear fit to the values in the Nova Scotia Normal Yield tables [42] around the early, on-time and late harvest ages. However, since these are based on diameter, they overestimate the yields. Thus, we have assumed only 60% yields for softwood logs with the remainder going to studwood, an 80% yield of total studwood with the remainder going to pulp and a 90% yield of pulpwood volume. Similarly, for hardwood we used 40%, 70%, and 80%. This is obviously a rough estimate for these yields and can be improved upon with real data.

Table 9: Yield table calculation

Yield table name	Product Name	Formula
SVol	Softwood	$(\text{Softwood \%}) \times (\text{Total volume per acre})$
HVol	Hardwood	$(1 - \text{Softwood \%}) \times (\text{Total volume per acre}) \times 0.6$
-----	pctLogs	$-0.058278811 + 0.039105148 \times LC + 0.002600375 \times iageH$
-----	studLogs	$0.410286731 + 0.007991919 \times LC + 0.00113054 \times iageH$
SLvol	sLog	$\text{pctLogs} \times \text{SVol} \times 0.60$
SSvol	sStudLog	$(0.40 \times \text{pctLogs} \times \text{Svol} + \text{pctStud} \times \text{svol}) \times 0.8$
SPvol	sPlpLog	$(\text{SVol} - \text{SLvol} - \text{SSvol}) \times 0.9$
HLvol	hLog	$0.4 \times \text{pctLogs} \times \text{HVol}$
HSvol	hStudLog	$(0.6 \times \text{pctLogs} \times \text{HVol} + \text{pctStud} \times \text{HVol}) \times 0.7$
HPvol	hPlpLog	$(\text{HVol} - \text{HLvol} - \text{HSvol}) \times 0.8$

Table 10: Yield table sample

<b>I</b>	<b>K</b>	<b>T</b>	<b>SVol</b>	<b>HVol</b>	<b>SPvol</b>	<b>SSvol</b>	<b>SLvol</b>	<b>HPvol</b>	<b>HSvol</b>	<b>HLvol</b>
1	1	2	68.97	2.18	20.62	34.46	11.6	0.72	1.04	0.24
1	1	13	172.43	5.45	51.55	86.15	29	1.79	2.59	0.61
1	2	2	68.97	2.18	20.62	34.46	11.6	0.72	1.04	0.24
1	2	15	240.82	7.61	64.86	124.5	44.25	2.33	3.77	0.93
1	3	2	68.97	2.18	20.62	34.46	11.6	0.72	1.04	0.24
1	3	16	256.5	8.1	65.28	134.84	49.14	2.38	4.09	1.03
1	4	2	68.97	2.18	20.62	34.46	11.6	0.72	1.04	0.24
1	5	4	96.33	3.04	25.94	49.8	17.7	0.93	1.51	0.37
1	5	15	172.43	5.45	51.55	86.15	29	1.79	2.59	0.61
1	6	4	96.33	3.04	25.94	49.8	17.7	0.93	1.51	0.37
1	6	17	240.82	7.61	64.86	124.5	44.25	2.33	3.77	0.93

#### 4.2.2. Plant data

Different types of capacities with a variety of possible technologies exist in the forest industry. For each case, there are different inputs, final products, by-products, installation cost, and fixed and variable operating costs. The Different types of capacities that are considered in this research, their inputs, and outputs are presented in Table 11. There are six types of mills in this experiment, two types of pulp mill, three types of sawmill, and one BioEnergy plant. In sawmills the input logs are processed into lumber. In pulp mills the fibers in the logs or chips are extracted. This product can be further processed to produce paper. The pulp mills can generally be categorized into two types based on their process: mechanical pulp mills or TMP mills, and chemical pulp mills or Kraft mills. BioEnergy mills in this data set are mills which can produce electricity from logs and the by-products from other mills.

Table 11: Different facilities, their Inputs, and their outputs

Plant Name	Technology	Log Input	By-product Input	Final Product	By-product Output
sPlpM	Kraft mill	sPlpLog, sStudLog	sChip	SPlp	Bark
hPlpM	TMP mill	hPlpLog, hStudLog, hLog	hChip	hPlp	Bark
sStudM	Softwood stud mill	sStudLog, sLog		sStud	Bark, sChip
sSawM	Softwood Sawmill	sLog		sLumber	Bark, sChip
hSawM	Hardwood sawmill	hLog		hLumber	Bark, hChip
BioEnergy	BioEnergy mill	sPlpLog, hPlpLog, sStudLog, sLog, hStudLog, hLog	sChip, hChip, Bark	Energy	Bark

There are different costs for each mill: installation cost, fixed operating cost, and variable operating cost. Some of the parameters needed to calculate these costs are presented in Table 12 .

Some of these data came from confidential sources and experts. For the capacity installation cost, first the nonlinear cost function is estimated. For estimation, a base point with known capacity and capacity expansion cost is considered. It is also assumed that the capacity cost function is estimated by  $kx^\alpha$ , in which  $x$  is the capacity. The value of  $\alpha$  is estimated for thirty six different products in the chemical and metal industry. The average was equal to 0.68, and the median was equal to 0.66 [46]. In this thesis we assume that the value of  $\alpha$  is equal to 0.67. Parameter  $k$  is calculated for each plant using the base point. For example, for sPlpM the base point capacity is 200000, and the base point cost is equal to \$505512651. Based on the capacity cost function,  $\log(505512651) = \log(k) + 0.67 \log(200000)$ , and  $k$  is equal to 141919.

Table 12: Data for calculating Capacity installation and operating costs

plant	Base capacity	Base cost	Max capacity	Min capacity	Fix operating cost	Variable operating Cost per unit
sPlpM	200000	505512651	500000	50000	8994742	100.6
hPlpM	300000	238009991	800000	50000	12757402	97.8
sStudM	200000	60000000	500000	40000	4800000	30
sSawM	100000	107017397	500000	50000	4800000	30
hSawM	100000	107017397	800000	50000	4800000	30
BioEnergy	84000	37746844	420000	3000	896188	5.6

Knowing all the parameters of the capacity cost function, it is possible to consider different capacity options and their cost. Eight different points, between maximum and minimum capacity, are considered as these options. The different capacity options and their costs for each type of mill are presented in Table 13.

Table 13: Different capacity options and their installation costs

Plant	option	1	2	3	4	5	6	7	8
sPlpM	Capacity	50000	114286	178571	242857	307143	371429	435714	500000
	Cost	199687300	347452265	468548513	575738978	673842849	765344558	851737459	934007676
hPlpM	Capacity	50000	157143	264286	371429	478571	585714	692857	800000
	Cost	71652676	154326292	218631070	274624302	325451924	372625015	417017027	459190401
sStudM	Capacity	40000	105714	171429	237143	302857	368571	434286	500000
	Cost	20409174	39139457	54110429	67251498	79227248	90368016	100868334	110854962
sSawM	Capacity	50000	114286	178571	242857	307143	371429	435714	500000
	Cost	67259862	117030934	157819292	193923820	226967748	257787897	286887267	314598009
hSawM	Capacity	50000	157143	264286	371429	478571	585714	692857	800000
	Cost	67259862	144865003	205227445	257787897	305499428	349780476	391450945	431038794
BioEnergy	Capacity	3000	62571	122143	181714	241286	300857	360429	420000
	Cost	4048372	30987118	48507716	63299444	76542985	88738204	100156257	110965057

To calculate fixed and variable operating costs for each type of mill, the operating cost at a base point is considered. This base point is different from the capacity expansion base point, and it is used for operating costs. A nonlinear cost function is estimated using the base point. The cost of three different points on this function is calculated and a line is fit to them using linear regression. The intercept of that line is considered as the fixed operating cost and the slope of it, the variable operating cost.

For example, for a sawmill with the capacity of 100000 mbf, the annual operating costs are equal to \$8180000. As mentioned before, this number came from a confidential resource. The operating cost estimated by  $kx^\alpha$  in which  $x$  is the capacity and  $\alpha$  is equal to 0.5. Using the base point parameter  $k$  is equal to 25867. The operating costs of two other points with the capacity of 200000 and 300000 mbf are calculated. Using a linear regression the intercept and slope of this line is calculated (Figure 11). The intercept, which is approximately equal to \$4,800,000 is the fixed cost, and the slope, which is about 30, is the variable cost per unit. These numbers are used for sSawM, hSawM, and sStudM.

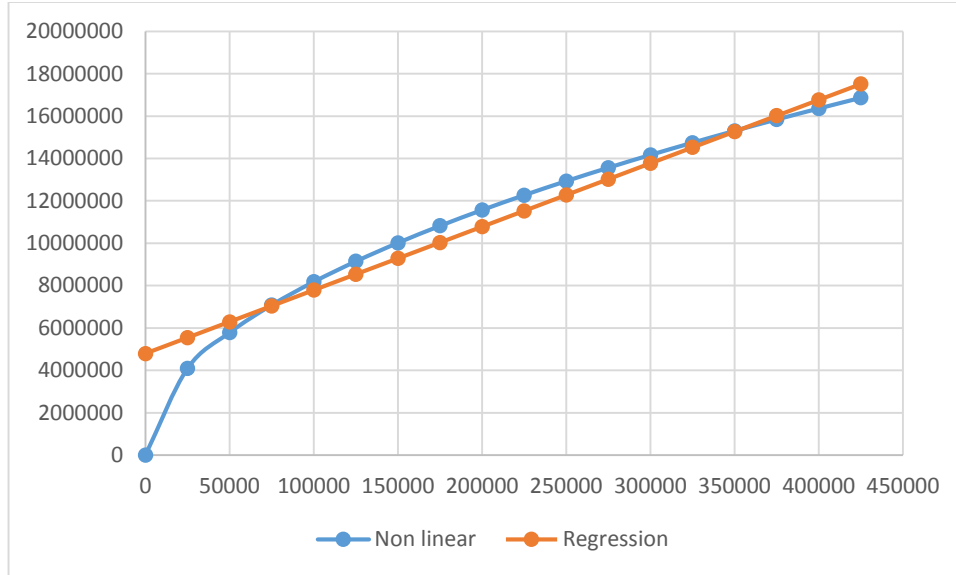


Figure 11: Nonlinear, and linear approximation of operating cost for a sawmill

For each mill type, we have defined eight possible locations, located at the intersection points of the regions. The coordinates of these locations are presented in Table 14. The distance between different points in the network is calculated based on Euclidean distance.

Table 14: potential mill locations

Location	X	Y
1	50	50
2	50	100
3	100	50
4	100	100
5	150	50
6	150	100
7	200	50
8	200	100

#### 4.2.3. Products and flow data

To define the flow of material in the network, which includes the transformations of inputs to outputs in plants, the yields and conversion rates are necessary. The first set of flows in the system is the flows of logs from the forest to mills. Not all types of logs will be accepted in a specific type of mill. For each type of log, at each type of mill, there is a multiplier which transforms one unit of log to one unit of operating level at that mill. Table



15, shows the different possible flows of logs to mills, and the multiplier corresponding to them.

Table 15: Log flow

#	LogType	Unit	MillType	Operating level unit	MultL
1	sPlp	m <sup>3</sup>	sPlpM	Ton	0.14
2	sPlp	m <sup>3</sup>	BioEnergy	MWh	0.57
3	sStud	m <sup>3</sup>	sPlpM	Ton	0.14
4	sStud	m <sup>3</sup>	sStudM	Mbf	0.27
5	sStud	m <sup>3</sup>	BioEnergy	MWh	0.57
6	sLog	m <sup>3</sup>	sSawM	Mbf	0.31
7	sLog	m <sup>3</sup>	sStudM	Mbf	0.27
8	sLog	m <sup>3</sup>	BioEnergy	MWh	0.57
9	hPlp	m <sup>3</sup>	hPlpM	Ton	0.39
10	hPlp	m <sup>3</sup>	BioEnergy	MWh	0.57
11	hStud	m <sup>3</sup>	hPlpM	Ton	0.39
12	hStud	m <sup>3</sup>	BioEnergy	MWh	0.57
13	hLog	m <sup>3</sup>	hSawM	Mbf	0.31
14	hLog	m <sup>3</sup>	hPlpM	Mbf	0.39
15	hLog	m <sup>3</sup>	BioEnergy	MWh	0.57

Another flow in the system is the flow of intermediate products from one mill to another. In these sample data, three types of intermediate products exist in the system: hardwood chips, softwood chips, and bark. Table 16 shows the different possible flows of the intermediate products. Each record shows the intermediate product, the mill which may produce it and a possible destination mill. The output yield shows the fraction of the input wood which turn into the intermediate product. Input yield shows the contribution of one cubic meter of intermediate product to one unit of the destination mill's operating level.

Table 16: Intermediate product flow

#	Product	Unit	Mill_From	Mill_To	Output yield	Unit	Input yield	Unit
1	hChip	Ton	hSawM	hPlpM	0.42	m <sup>3</sup>	0.39	Ton
2	sChip	Ton	sSawM	sPlpM	0.42	m <sup>3</sup>	0.14	Ton
3	hChip	Ton	hSawM	BioEnergy	0.42	m <sup>3</sup>	0.57	MWh
4	sChip	Ton	sSawM	BioEnergy	0.42	m <sup>3</sup>	0.57	MWh
5	Bark	Ton	hSawM	BioEnergy	0.1	m <sup>3</sup>	0.57	MWh
6	Bark	Ton	sSawM	BioEnergy	0.1	m <sup>3</sup>	0.57	MWh
7	Bark	Ton	sPlpM	BioEnergy	0.1	m <sup>3</sup>	0.57	MWh
8	Bark	Ton	hPlpM	BioEnergy	0.1	m <sup>3</sup>	0.57	MWh
9	Bark	Ton	sStudM	BioEnergy	0.1	m <sup>3</sup>	0.57	MWh
10	Bark	Ton	BioEnergy	BioEnergy	0.1	m <sup>3</sup>	0.57	MWh
11	sChip	Ton	sStudM	BioEnergy	0.49	m <sup>3</sup>	0.57	MWh
12	sChip	Ton	sStudM	sPlpM	0.49	m <sup>3</sup>	0.14	Ton

The last flow in the system is the flow of final products from each mill. The scope of this research is not to define the flow of detailed final products, but the main stream of products which have approximately the same raw material, process, and value. For example, we do not distinguish between 6 inch lumber and 12 inch lumber made in a sawmill. The data needed in this part are the main products and their approximate prices. In this data sample, all the products aggregated into one final product for each type of mill. Table 17 shows the final products and their unit, and price in the system.

Table 17: final product for each type of mill and their unit and price

#	Final Product	Mill Type	Unit	Price
1	sPlp	sPlpM	Ton	500
2	hPlp	hPlpM	Ton	800
3	sStud	sStudM	Mbf	250
4	sLumber	sSawM	Mbf	350
5	hLumber	hSawM	Mbf	550
6	Energy	BioEnergy	MWh	150

### 4.3. Experimental results

In this section, different numerical experiments for the separate and integrated approaches are proposed. Based on these experiments, the approaches are compared against each other using different measures, including: the net present profit, amount of harvest, harvesting pattern, and installed capacities. In the first section, one of the samples is analyzed in detail. In the second section to check the stability of the results, 5 more samples with different forests, are analyzed. In the last section, the separate and integrated approaches are investigated in different pricing scenarios.

To solve the mathematical models, the Gurobi solver with C++ interface is used [47]. Different data and parameters which were explained in the previous sections are stored in different text files. Using C++, these parameters and data are read from these files and saved as different variables. All the decision variables and constraints are built separately and passed to Gurobi. The model is solved using Gurobi and the results are saved in an excel file. This procedure and some sample codes are explained briefly in Appendix B.

#### 4.3.1. The analyses of the integrated and separate approaches

In this section, the two approaches are compared and analyzed in detail. The analysis includes the comparison of the objective function, harvesting level and pattern, the installed capacities and their locations in two different approaches.

Table 18 shows the objective function and its components for the separate and integrated approaches. The integrated approach, results in better net present profit. Although, the revenue gained from selling the final product in the integrated approach is less than the separate approach, the different costs are also lower. Total alpha is equal to 0, which shows that the non-declining-yield constraint is satisfied in both approaches. It is worthwhile to explain that the objective function in this research considers the whole system profit and not each of the element's profit. In other words, it does not provide how the profit split between forest and mills.

Table 18: The objective function and its different parts in two approaches (in dollars except Total Alpha)

Approach	Integrated Approach	Separate Approach
OBJ	1.87E+09	1.70E+09
Total Discounted Final Revenue	2.72E+10	2.78E+10
Total Discounted Transportation Cost	1.03E+09	1.12E+09
Total Discounted Harvesting Cost	2.88E+09	3.00E+09
Total Discounted Landowner Cost	1.86E+09	1.88E+09
Total Capacity Cost	1.78E+09	1.82E+09
Total Discounted Fixed Operating Cost	4.61E+08	4.72E+08
Total Discounted Variable Operating Cost	1.51E+09	1.53E+09
Total Alpha	0	0

Table 19 and Table 20 show the amount of harvest from softwood and hardwood in each planning period using the integrated and separate approaches, respectively. These amounts remain constant in all 21 periods. The gap between the softwood and hardwood harvest is consistent with the generated forest, in which only 20% of the stands are hardwood. Figure 12 and Figure 13 show the difference in the amount of softwood and hardwood harvest graphically. Non-declining yield constraints result in the same amount of harvest in all 21 planning periods.

For this problem set, in the integrated approach the amount of harvest from softwood is 95% of the separate approach. This number is equal to 98% for hardwood. Although, the amount of harvest, in the integrated approach is less than in the separate approach, the gained profit of the system is higher. In this problem set, the industry is quite profitable and it is reasonable to harvest more to gain more profit. This is the reason why the harvest gap between the integrated and separate approaches is small. In section 4.3.3, some cases are presented in which the industry is not profitable in comparison with the current case. This will result in more harvest reduction in the integrated approach.

Table 19 : Amount of harvest in m<sup>3</sup> for 6 planning periods in the integrated approach

Period	1	2	3	4	5	6
SW	2.76E+07	2.76E+07	2.76E+07	2.76E+07	2.76E+07	2.76E+07
HW	5.44E+06	5.44E+06	5.44E+06	5.44E+06	5.44E+06	5.44E+06

Table 20 : Amount of harvest in m<sup>3</sup> for 6 planning periods in the separate approach

Period	1	2	3	4	5	6
SW	2.89E+07	2.89E+07	2.89E+07	2.89E+07	2.89E+07	2.89E+07
HW	5.53E+06	5.53E+06	5.53E+06	5.53E+06	5.53E+06	5.53E+06

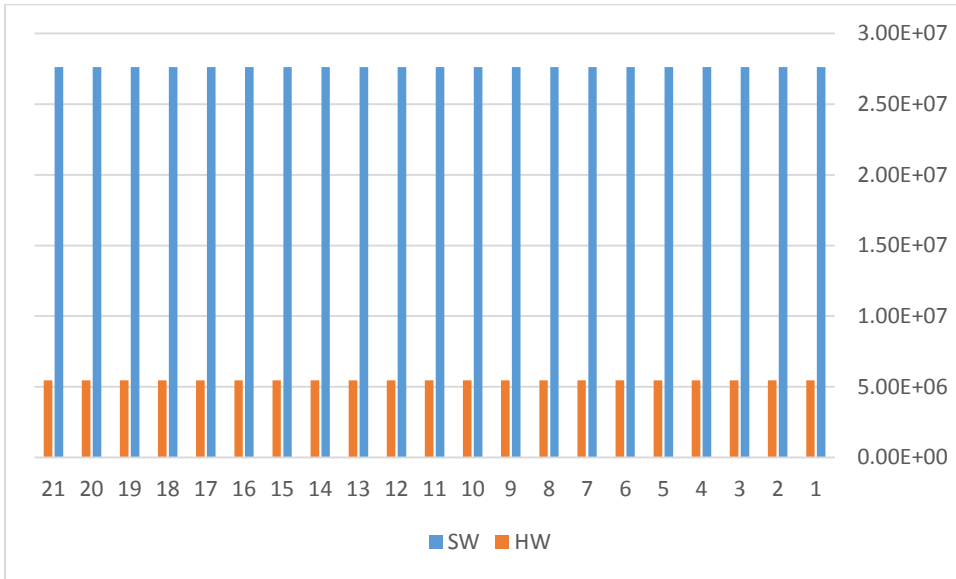


Figure 12: SW/HW harvest in each planning period in the integrated approach

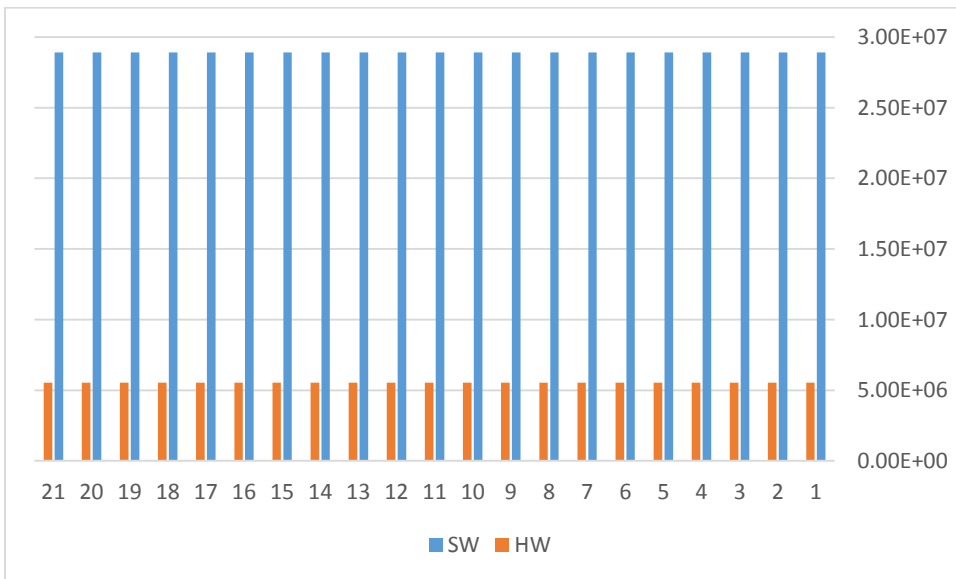


Figure 13: SW/HW harvest in each planning period in the separate approach

Figure 14 and Figure 15 show the amount Softwood harvest in 21 planning periods, separated by regions, using the integrated and the separate approaches, respectively. Figure 16 and Figure 17 are the same diagrams for hardwood harvest.

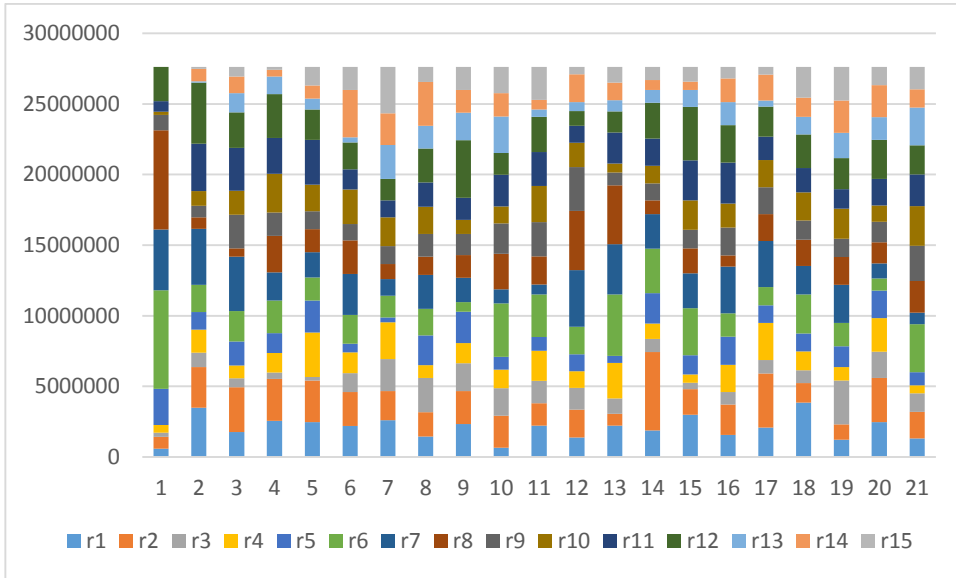


Figure 14: Amount of SW harvest in each planning period from each region (Integrated Approach)

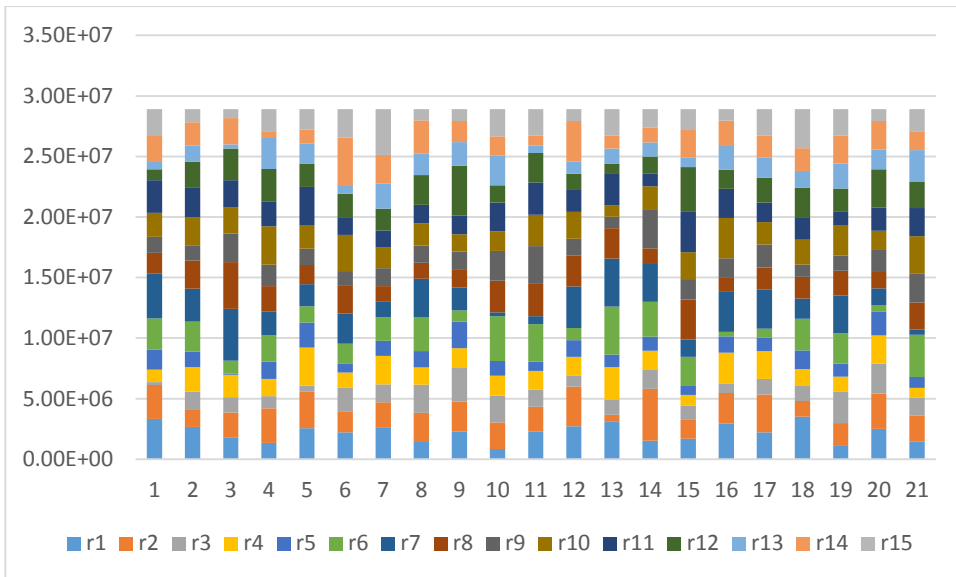


Figure 15: Amount of SW harvest in each planning period from each region (Separate Approach)

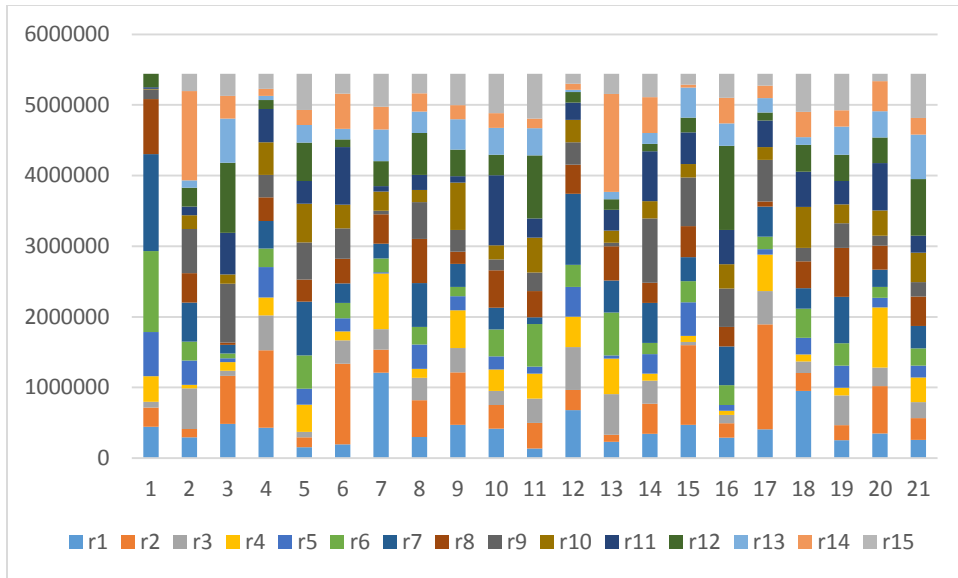


Figure 16: Amount of HW harvest in each planning period from each region (Integrated Approach)

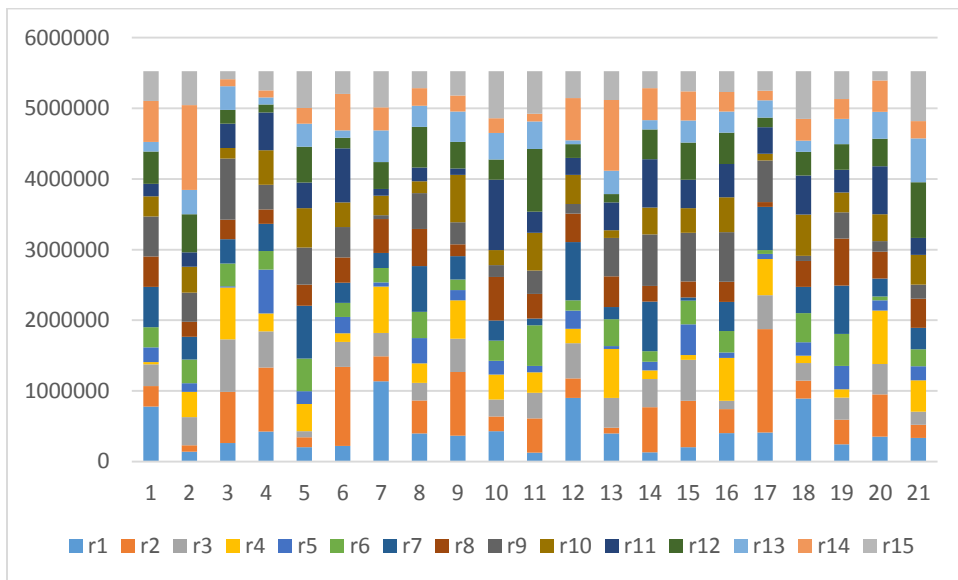


Figure 17: Amount of HW harvest in each planning period from each region (Separate Approach)

By analyzing Figure 14 to Figure 17, the different patterns of harvest in the separate and integrated approaches can be noticed. The harvest pattern is different in the two approaches, especially in the first couple of periods. For example, the amount of harvest in some regions in the integrated approach is equal to 0 or much smaller than in the separate approach. The model tries to minimize the net present value of transportation costs which results in extensive harvest in the regions which are close to the mills and low harvest in the areas which are further from the mills. Figure 18 and Figure 19 show the variation of

harvest in the different regions more clearly over time. The amount of harvest from regions that are far from installed capacities is less than in the same regions in the separate approach. For example, the installed capacities, which are mostly in location 3, are far from regions 14 and 15 (Figure 20). This distance results in less harvest in this region in comparison with other areas in the same approach and the same areas in the separate approach.

There are some issues that are worthwhile to discuss. Firstly, these results show that the effect of capacity expansion on harvesting pattern cannot be ignored, and can be used to design an efficient system. Secondly, the symmetric property of the forest area in the data set, which may not happen in reality, may have an effect on this pattern variation. Thirdly, the objective function of the model is to maximize the net present profit in the system, and the interest rate in the current sample is equal to 10%, which results in a decreasing cash flow from period one to period six. To increase the net profit in the first period, the model may increase the harvest to gain more profit, or decrease different costs. Increasing the harvest only in the first period will penalize the model because of non-declining-yield constraints, and it may increase all the other costs. At the same level of harvest, with defined set of capacities, the only cost that can be decreased is the transportation cost, which results in an extensive harvest from the areas which are closer to the mills, especially in the first period.

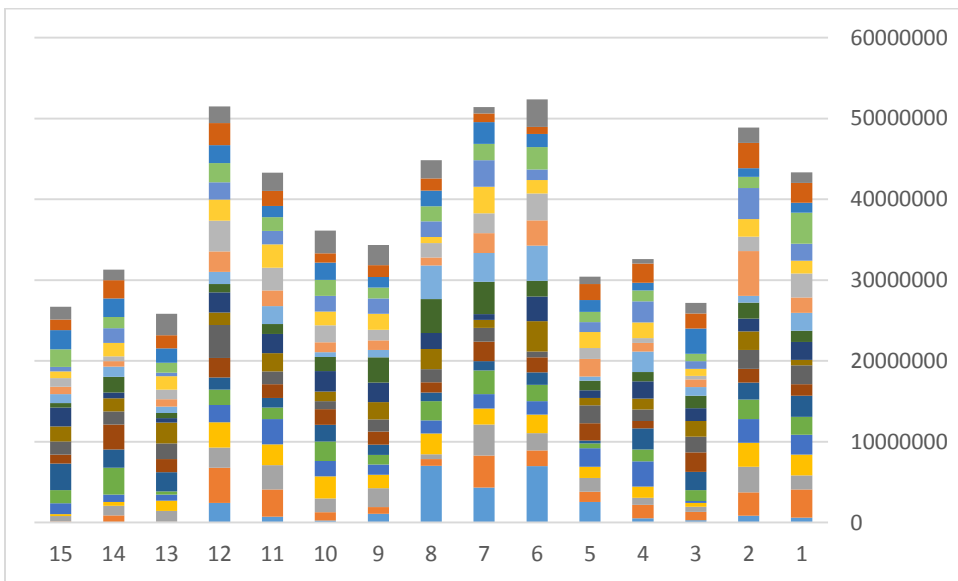


Figure 18: Amount of SW harvest from each region in each planning period (Integrated Approach)



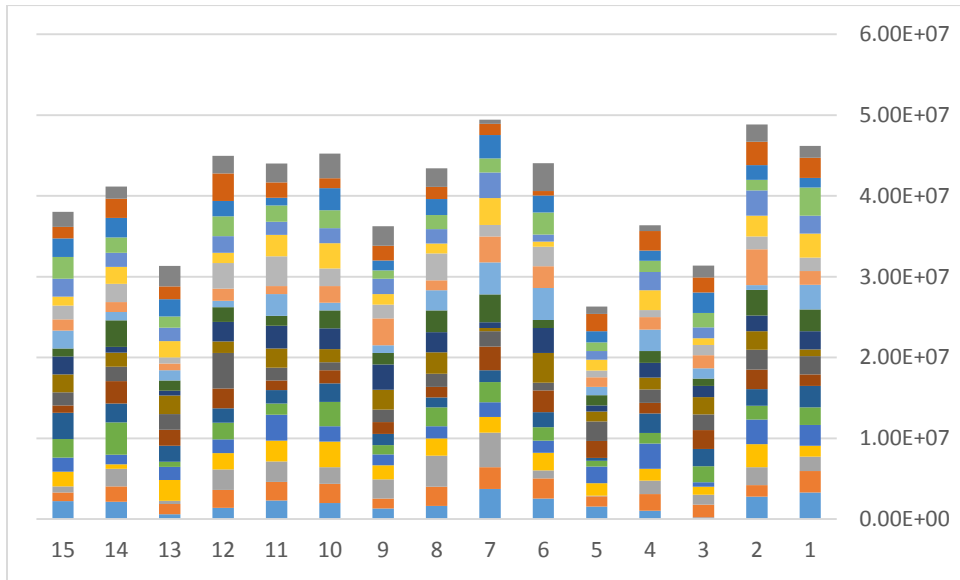


Figure 19: Amount of SW harvest from each region in each planning period (Separate Approach)

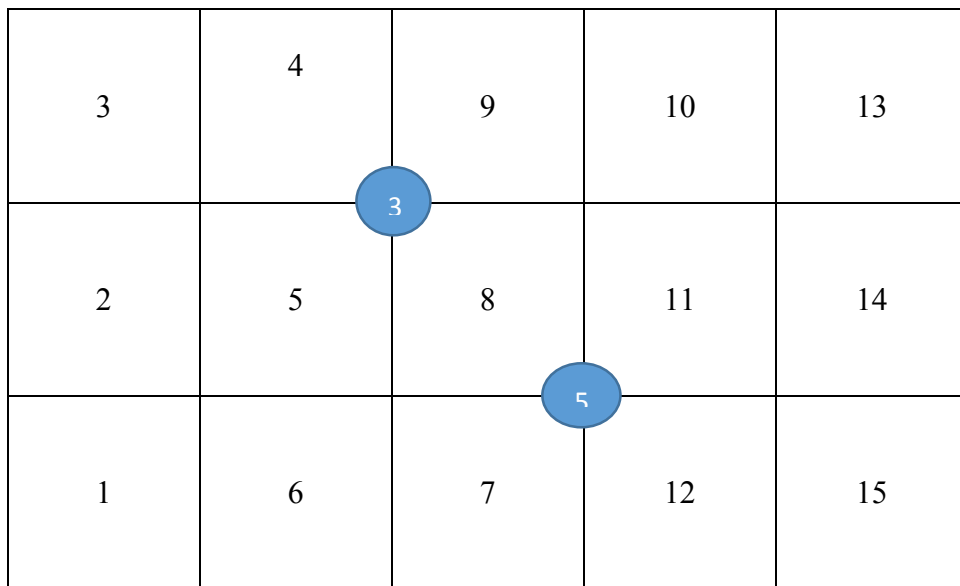


Figure 20: Different region and installed capacity locations (Integrated Approach)

Table 21 and Table 22 show the installed mills, their locations, capacity, and average operating levels in the first six periods for the integrated and separate approaches, respectively. In this data set, the installed capacities in the two approaches are almost the same. In the separate approach, there is an extra BioEnergy mill. This is because we have more wood harvested in the separate approach, and based on the cost and profit, it is more

profitable to open a new BioEnergy plant. As mentioned earlier in the section, in the current data set, the industry is quite profitable. This reduces the harvest gap, and the difference in installed capacities, in two different approaches.

Table 21: The installed mill, their location, capacity, and average operating level (Integrated Approach)

Mill	Location	Capacity	Unit	Average Operating Level					
				1	2	3	4	5	6
sPlpM	3	4.36E+05	Ton	4.19E+05	4.25E+05	4.28E+05	4.36E+05	4.36E+05	4.36E+05
hPlpM	3	4.79E+05	Ton	4.01E+05	3.99E+05	3.99E+05	3.95E+05	3.95E+05	3.96E+05
sStudM	3	5.00E+05	Mbf	5.00E+05	5.00E+05	5.00E+05	5.00E+05	5.00E+05	4.78E+05
sStudM	5	3.69E+05	Mbf	3.69E+05	3.56E+05	3.49E+05	3.02E+05	3.01E+05	3.23E+05
sSawM	3	4.36E+05	Mbf	4.27E+05	4.13E+05	4.02E+05	3.52E+05	3.53E+05	3.53E+05
BioEnergy	3	4.20E+05	MWH	3.68E+05	3.67E+05	3.67E+05	4.20E+05	4.20E+05	4.20E+05

Table 22: The installed mill, their location, capacity, and average operating level (Separate Approach)

Mill	Location	Capacity	Unit	Average Operating Level					
				1	2	3	4	5	6
sPlpM	3	4.36E+05	Ton	4.36E+05	4.36E+05	4.36E+05	4.36E+05	4.36E+05	4.36E+05
hPlpM	3	4.79E+05	Ton	4.01E+05	4.04E+05	4.06E+05	4.00E+05	4.01E+05	4.02E+05
sStudM	3	5.00E+05	Mbf	5.00E+05	5.00E+05	5.00E+05	4.65E+05	5.00E+05	4.67E+05
sStudM	5	3.69E+05	Mbf	3.33E+05	3.59E+05	3.69E+05	3.69E+05	3.38E+05	3.69E+05
sSawM	3	4.36E+05	Mbf	3.72E+05	3.94E+05	4.36E+05	3.59E+05	3.68E+05	3.64E+05
BioEnergy	3	4.20E+05	MWH	4.01E+05	3.71E+05	3.77E+05	4.11E+05	3.99E+05	4.05E+05
BioEnergy	8	1.22E+05	MWH	1.22E+05	1.11E+05	6.97E+04	1.22E+05	1.22E+05	1.22E+05

Figure 21 and Figure 22 show the actual cash flow of total revenue per period for the integrated and separate approaches, respectively. In the integrated approach, as the harvesting and capacity expansion are decided simultaneously, the net present value calculation with 10% interest rate results in constant decrease in the cash flow. In the separate approach, the amount of harvest is defined using the forest management mathematical model, and then in the second phase the model tries to optimize the net present value which is constrained by the amount of harvest. Although the constant decrease cannot be seen in the separate approach, the cash flows in the last 3 periods are

generally less than in the first planning periods. This issue is a challenge for the forest management. Does the non-declining-yield constraint result in a financially sustainable system? To have a financially sustainable system, financial issues should be considered in the forest management process, which means that the separate approach should be revised.

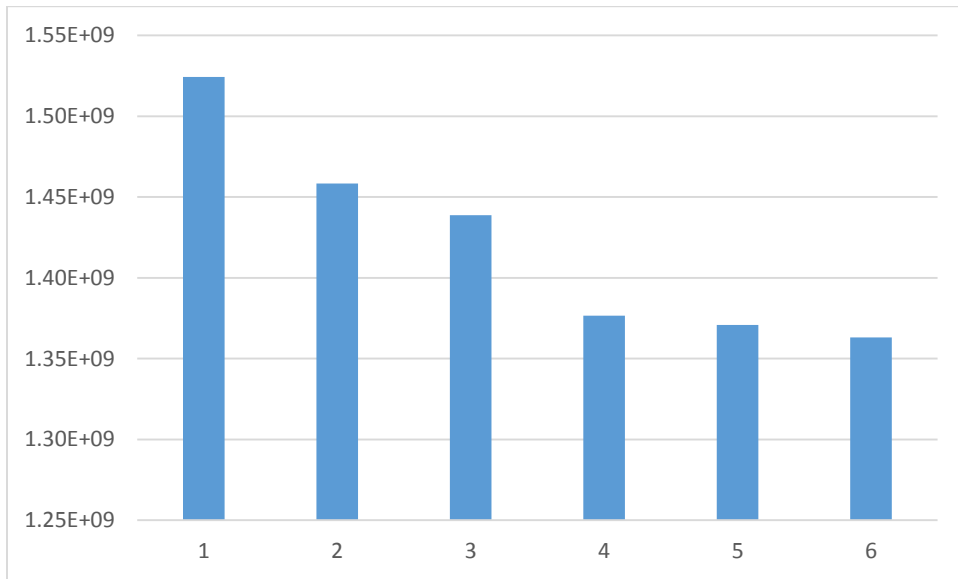


Figure 21: Cash Flow of total revenue per period (Integrated Approach)

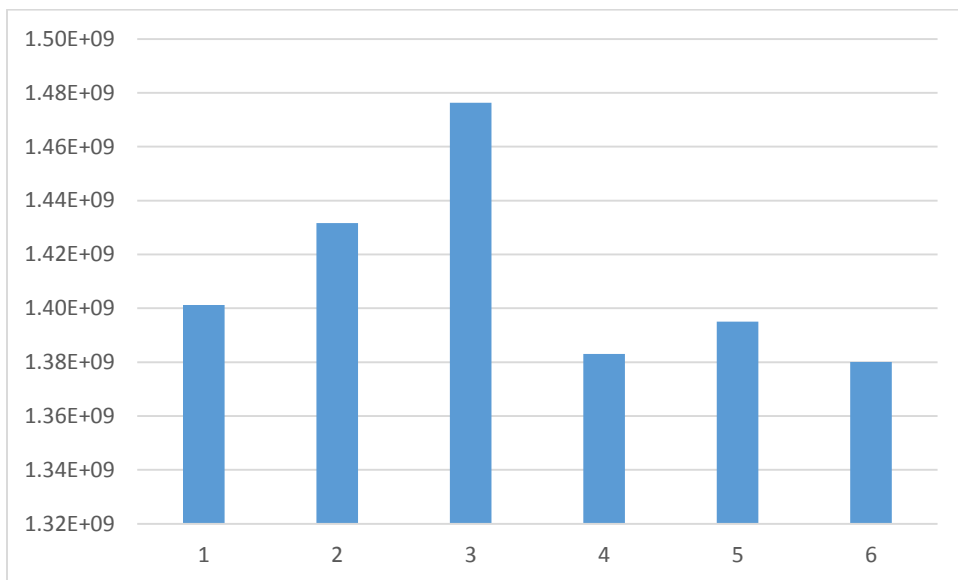


Figure 22: Cash Flow of total revenue per period (Separate Approach)

### 4.3.2. Different forest scenarios

The analysis in the previous section was based on one problem set. In this section, we examine five other problem sets in an effort to test the superiority of the integrated approach over the separate one over this broader sample of forests. S0 is the sample which was explained in section 4.3.1, and the rest of them are named from S1 to S5. All these samples are generated based on the same distributions which are explained in section 4.2.1. Although the total forest in the different scenarios is almost the same, different region characteristics maybe different from each other. The total area of each region in different scenarios are presented in Table 23. The histograms of Age, site class, cover type, and stocking by region for scenario S0 is presented in Figure 23, Figure 24, Figure 25, and Figure 26, respectively.

Table 23: Total area of different regions in different scenarios

<b>Region</b>	<b>S0</b>	<b>S1</b>	<b>S2</b>	<b>S3</b>	<b>S4</b>	<b>S5</b>
<b>1</b>	218200.3	147842.8	160797.5	165579.7	184845.6	170585.3
<b>2</b>	255930.1	224594.2	235376.2	248858.9	234554.1	246268.9
<b>3</b>	186551.4	180923.1	166620.3	171945.0	182005.6	182487.7
<b>4</b>	204995.5	172746.0	208228.1	161444.9	187185.8	194706.3
<b>5</b>	143803.4	157841.8	143913.2	151929.2	149609.9	169818.8
<b>6</b>	237718.9	238274.9	213717.9	193207.1	213384.3	200057.9
<b>7</b>	215048.3	198214.4	188158.8	239850.9	238666.8	217143.5
<b>8</b>	204142.3	204584.6	247201.8	191646.0	210281.8	209433.4
<b>9</b>	203436.4	216366.6	197026.3	241343.2	198883.8	251506.4
<b>10</b>	208373.3	176368.2	184227.0	179913.7	153182.4	147199.1
<b>11</b>	212779.7	217863.1	164031.6	211675.9	204833.4	205672.7
<b>12</b>	211337.2	215639.5	214973.0	226170.6	222824.4	208084.2
<b>13</b>	154865.0	151271.3	207520.9	206313.2	212570.5	177599.5
<b>14</b>	210214.9	189329.7	195706.6	205631.9	232520.5	206972.3
<b>15</b>	212143.4	239816.4	204177.4	208853.9	254191.2	272057.4
<b>Total</b>	3079540	2931677	2931677	3004364	3079540	2787536

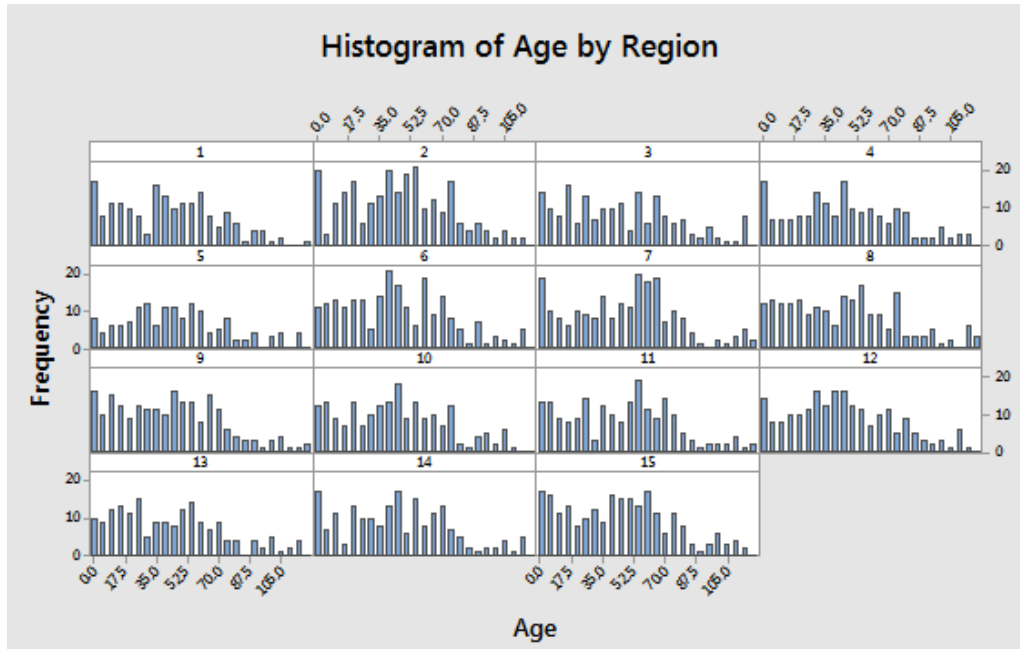


Figure 23 : Histogram of age by region for scenario S0

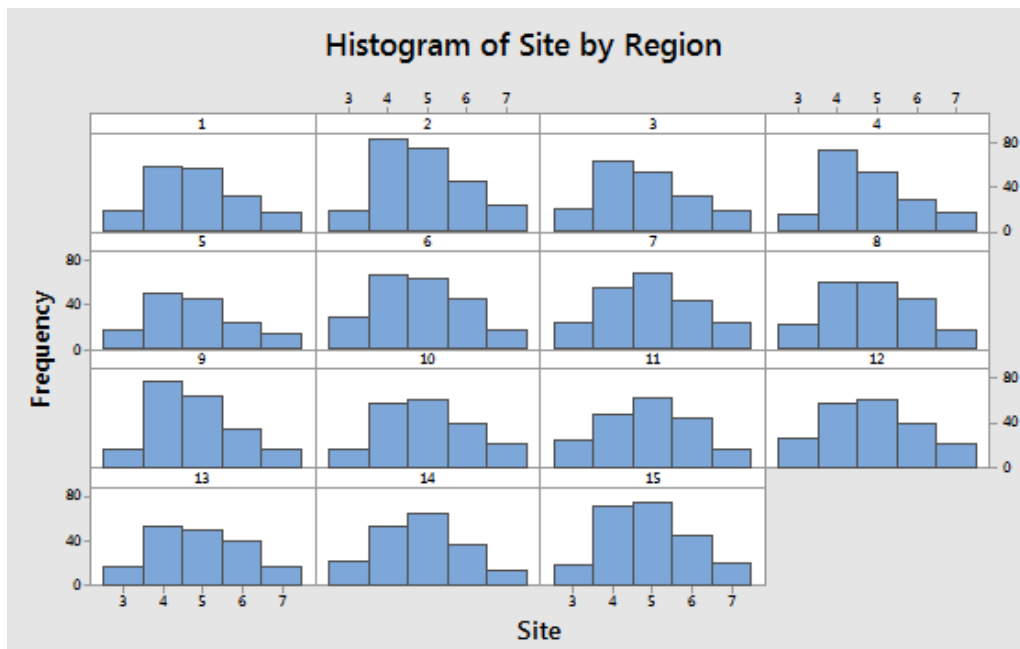


Figure 24: Histogram of site by region for scenario S0

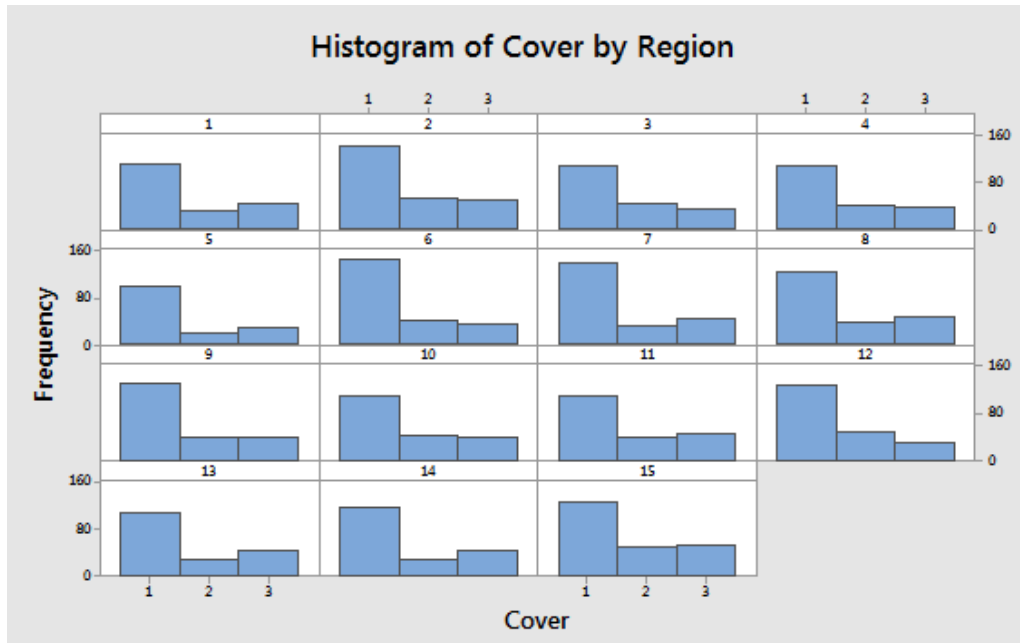


Figure 25: Histogram of cover by region for scenario S0

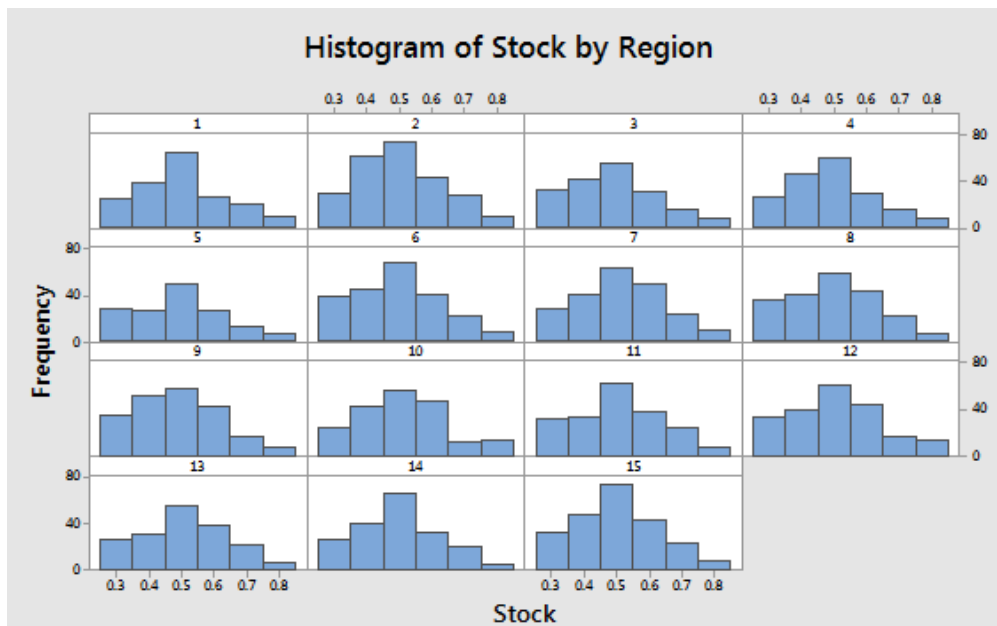


Figure 26: Histogram of stocking by region for scenario S0

The histograms of Age, site class, cover type, and stocking by scenario for region 1 are presented in Figure 27, Figure 28, Figure 29, and Figure 30, respectively. Although a characteristic in different scenarios is generated based on the same probability distribution, it looks different for each scenario.

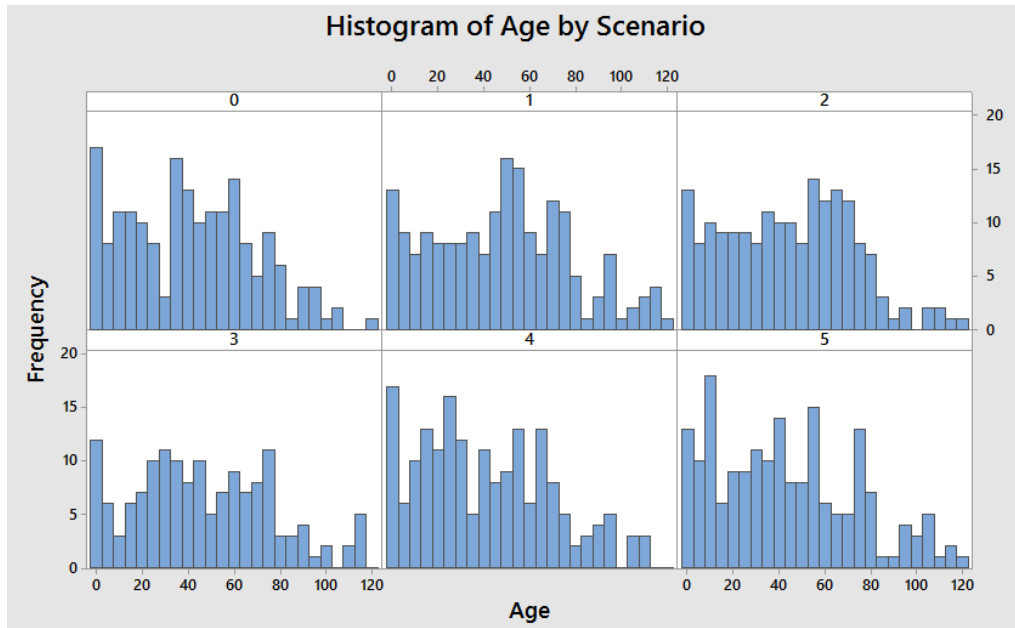


Figure 27: Histogram of age by scenario for region 1

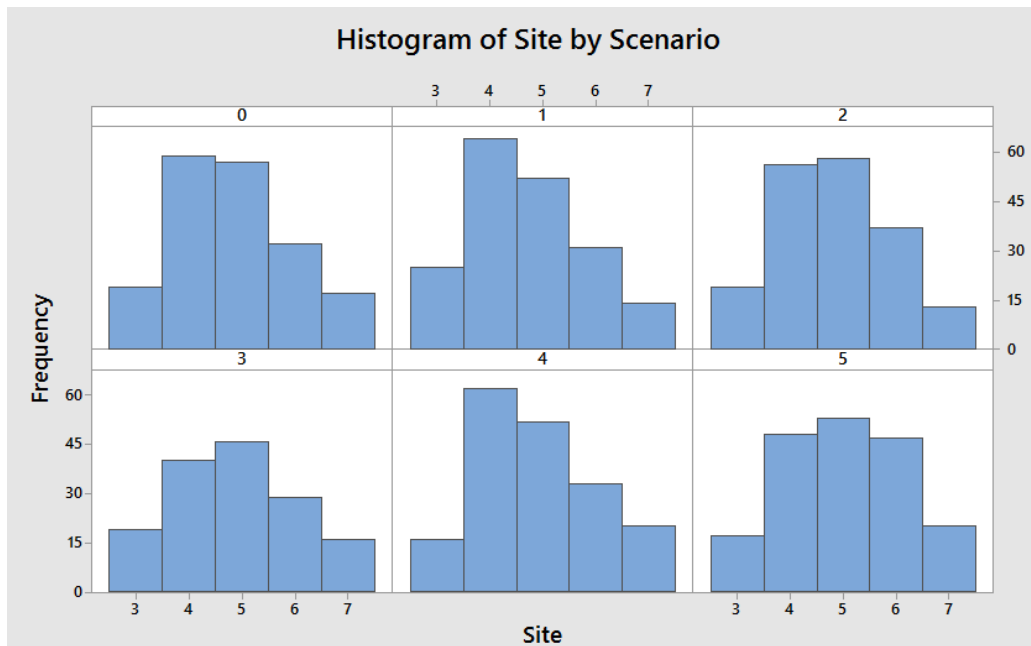


Figure 28: Histogram of site class by scenario for region 1

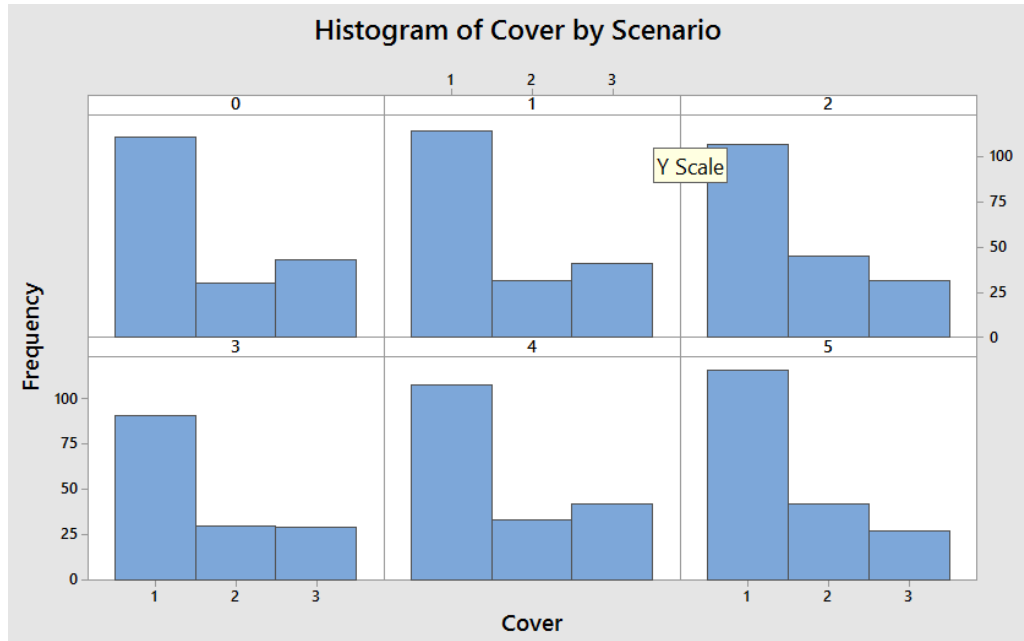


Figure 29: Histogram of cover type class by scenario for region 1

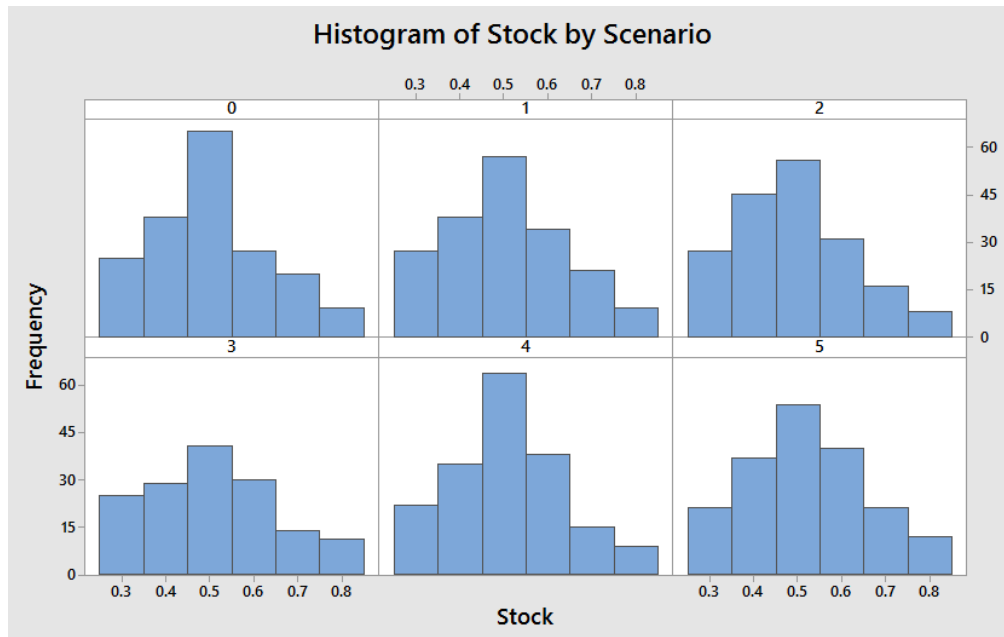


Figure 30: Histogram of stocking by scenario for region 1

Table 24 shows the net present profit in the separate and integrated approaches in the six different data sets. In all data sets, the integrated approach result in a better net profit in comparison with the separate approach.



Table 24: The objective function of the separate and integrated approach in different forest scenarios

S0			S1			S2		
Separate	Integrated	% difference	Separate	Integrated	% difference	Separate	Integrated	% difference
1.70E+09	1.87E+09	9.82%	1.73E+09	1.86E+09	7.35%	1.82E+09	1.92E+09	5.51 %
S3			S4			S5		
Separate	Integrated	% difference	Separate	Integrated	% difference	Separate	Integrated	% difference
2.05E+09	2.18E+09	6.79%	2.03E+09	2.16E+09	6.41%	1.87E+09	2.07E+09	11.07 %

Table 25 and Table 26 show the installed capacity in 6 different forest scenarios in the integrated and separate approaches. The installed capacities in these scenarios are quite similar to each other. The differences are mostly in the location of the mills. Because of the symmetric attribute of the forest area in this data set, there is not a significant difference between central locations 3, 4, 5, and 6. As Table 25 shows, all the capacities are installed in these locations. Note that in scenario S1 and S2 exactly the same capacities are built in the same locations in both the integrated and separate approaches. In Scenario S3, the same capacity sizes are built but their locations are different. In scenarios S0, S4 and S5, extra BioEnergy capacity is built in the separate approach.

Table 25 : Installed capacity in different forest scenarios (Integrated approach)

S0			S1			S2			Unit
Mill	location	Capacity	mill	location	Capacity	Mill	Location	Capacity	
sPlpM	3	4.36E+05	sPlpM	6	5.00E+05	sPlpM	5	5.00E+05	Ton
hPlpM	3	4.79E+05	hPlpM	6	4.79E+05	hPlpM	5	4.79E+05	Ton
sStudM	3	5.00E+05	sStudM	4	4.34E+05	sStudM	3	4.34E+05	Mbf
sStudM	5	3.69E+05	sStudM	6	5.00E+05	sStudM	5	5.00E+05	Mbf
sSawM	3	4.36E+05	sSawM	6	4.36E+05	sSawM	5	4.36E+05	Mbf
BioEnergy	3	4.20E+05	BioEnergy	6	4.20E+05	BioEnergy	5	4.20E+05	MW
S3			S4			S5			Unit
mill	Location	Capacity	mill	location	Capacity	Mill	location	Capacity	
sPlpM	5	5.00E+05	sPlpM	5	5.00E+05	sPlpM	6	5.00E+05	Ton
hPlpM	5	4.79E+05	hPlpM	5	4.79E+05	hPlpM	6	4.79E+05	Ton
sStudM	5	5.00E+05	sStudM	3	4.34E+05	sStudM	5	4.34E+05	Mbf
sStudM	6	4.34E+05	sStudM	5	5.00E+05	sStudM	6	5.00E+05	Mbf
sSawM	5	4.36E+05	sSawM	5	4.36E+05	sSawM	6	4.36E+05	Mbf
BioEnergy	5	4.20E+05	BioEnergy	5	4.20E+05	BioEnergy	6	4.20E+05	MW

Table 26: Installed capacity in different forest scenarios (Separate approach)

S0			S1			S2			Unit
Mill	location	Capacity	mill	location	Capacity	Mill	Location	Capacity	
sPlpM	3	4.36E+05	sPlpM	6	5.00E+05	sPlpM	5	5.00E+05	Ton
hPlpM	3	4.79E+05	hPlpM	6	4.79E+05	hPlpM	5	4.79E+05	Ton
sStudM	3	5.00E+05	sStudM	4	4.34E+05	sStudM	3	4.34E+05	Mbf
sStudM	5	3.69E+05	sStudM	6	5.00E+05	sStudM	5	5.00E+05	Mbf
sSawM	3	4.36E+05	sSawM	6	4.36E+05	sSawM	5	4.36E+05	Mbf
BioEnergy	3	4.20E+05	BioEnergy	6	4.20E+05	BioEnergy	5	4.20E+05	MWH
BioEnergy	8	1.22E+05							
S3			S4			S5			Unit
Mill	location	Capacity	mill	location	Capacity	Mill	Location	Capacity	
sPlpM	6	5.00E+05	sPlpM	5	5.00E+05	sPlpM	5	5.00E+05	Ton
hPlpM	6	4.79E+05	hPlpM	5	4.79E+05	hPlpM	5	4.79E+05	Ton
sStudM	4	4.34E+05	sStudM	3	5.00E+05	sStudM	3	4.34E+05	Mbf
sStudM	6	5.00E+05	sStudM	5	5.00E+05	sStudM	5	5.00E+05	Mbf
sSawM	6	4.36E+05	sSawM	5	4.36E+05	sSawM	5	4.36E+05	Mbf
BioEnergy	6	4.20E+05	BioEnergy	2	1.22E+05	BioEnergy	4	6.26E+04	MWH
			BioEnergy	5	4.20E+05	BioEnergy	5	4.20E+05	MWH

#### 4.3.3. Pricing Scenarios

In this section, the result of the models and the proposed approaches are compared at different pricing scenarios. S0 is the basic scenario which is explained in section 1.2.1. The rest of the scenarios are generated based on S0 (Table 27).

Table 27: Different pricing scenarios

Scenario	Definition
S0	The basic scenario
SP1	This scenario is an extreme case scenario in which the price of hardwood product increased by 20% and the price of softwood product decreased by 20%
SP2	In this scenario, the price of softwood product increase by 20% and hardwood product decreased by 20%
SP3	In this scenario, the price of lumber decreased by 20% and the price of pulp increased by 20%
SP4	In this scenario, the price of pulp decreased by 20% and the price of lumber increased by 20%
SP5	In this scenario, the price of energy increased by 50%

Table 28 shows the net present profit of the separate and integrated approaches and their difference percentage. The gap in the objective functions of separate and integrated

approaches in the second scenario is significant. This is because the softwood industry is not profitable in this scenario, and the forest in this data set mostly consists of softwood.

Table 28: The objective function of the separate and integrated approach in different pricing scenarios

S0			SP1			SP2		
Separate	Integrated	% difference	Separate	Integrated	% difference	Separate	Integrated	% difference
1.70E+09	1.87E+09	9.82%	1.64E+09	2.32E+09	41.20%	2.14E+09	2.30E+09	7.53%
SP3			SP4			SP5		
Separate	Integrated	% difference	Separate	Integrated	% difference	Separate	Integrated	% difference
2.43E+09	2.53E+09	4.29%	1.62E+09	1.77E+09	9.33%	2.81E+09	2.89E+09	2.72%

Figure 31 shows the amount of softwood and hardwood harvest in the separate and integrated approaches in different scenarios. As the same forest (S0) is used in all pricing scenarios, the amount of harvest in the separate approach is the same for all of them. Figure 31 shows that considering capacity decisions in forest management affects the amount of harvest. This effect in S1 is significant, as the industry is not profitable and harvesting more wood does not result in increasing the profit of the system.

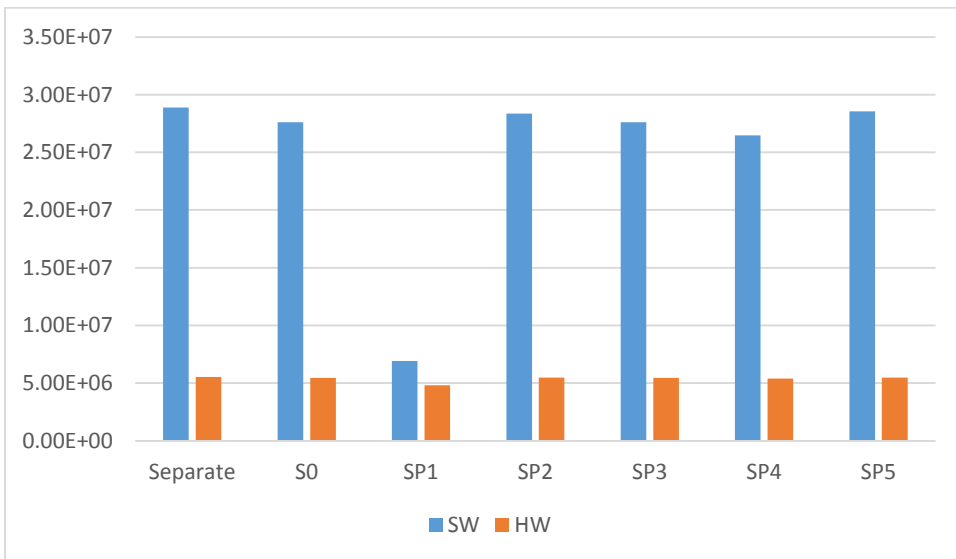


Figure 31: Amount of softwood and hardwood harvest per period in each pricing scenario

Table 29 and Table 30 show the installed capacities and their locations in different pricing scenarios, for integrated and separate approaches, respectively. The capacity unit for each type of mill is the same as previous tables, and it is not repeated due to space

limitation. In Scenario S1, the price of hardwood final products increased by 20% and the price of softwood products decreased by the same percentage. In this scenario, softwood pulp is not profitable in comparison with electricity. In the separate approach, the harvested wood is processed in the BioEnergy plant instead of sPlpM. In the integrated approach, the amount of harvest decreased extensively, as it is not profitable. The softwood and hardwood harvest in the integrated approach is equal to 24% and 87% of the separated approach, respectively. In terms of installed capacity, the softwood mills decreased in the integrated approach. In the separated approach, there is one hPlpM, two sStudM, and one sSawM. The rest of the wood is processed in six BioEnergy plants. In the integrated approach, there are one sStudM, one hPlpM and two BioEnergy plants. In both integrated and separate approaches, there is no sPlpM.

Table 29: Installed capacity in different pricing scenarios in the (Integrated approach)

S0			SP1			SP2		
Mill	location	Capacity	mill	location	Capacity	Mill	Location	Capacity
sPlpM	3	4.36E+05	hPlpM	5	3.71E+05	sPlpM	5	4.36E+05
hPlpM	3	4.79E+05	sStudM	3	3.03E+05	hPlpM	5	4.79E+05
sStudM	3	5.00E+05	BioEnergy	3	4.20E+05	sStudM	3	4.34E+05
sStudM	5	3.69E+05	BioEnergy	5	1.82E+05	sStudM	5	5.00E+05
sSawM	3	4.36E+05				sSawM	5	4.36E+05
BioEnergy	3	4.20E+05				BioEnergy	3	6.26E+04
						BioEnergy	5	4.20E+05
SP3			SP4			SP5		
Mill	location	Capacity	mill	location	Capacity	Mill	location	Capacity
sPlpM	3	4.36E+05	hPlpM	3	3.71E+05	hPlpM	5	4.79E+05
hPlpM	3	4.79E+05	sStudM	1	3.69E+05	sStudM	3	5.00E+05
sStudM	3	5.00E+05	sStudM	5	5.00E+05	sStudM	7	3.69E+05
sStudM	5	3.69E+05	sSawM	3	4.36E+05	sSawM	5	4.36E+05
sSawM	3	3.71E+05	hSawM	3	5.00E+04	BioEnergy	1	4.20E+05
BioEnergy	3	4.20E+05	BioEnergy	1	4.20E+05	BioEnergy	2	1.82E+05
			BioEnergy	2	4.20E+05	BioEnergy	3	4.20E+05
			BioEnergy	3	4.20E+05	BioEnergy	5	4.20E+05
			BioEnergy	5	4.20E+05	BioEnergy	7	4.20E+05
			BioEnergy	6	4.20E+05	BioEnergy	8	4.20E+05

Table 30: Installed capacity in different pricing scenarios (Separate approach)

S0			SP1			SP2		
Mill	location	Capacity	mill	location	Capacity	mill	Location	Capacity
sPlpM	3	4.36E+05	hPlpM	6	4.79E+05	sPlpM	5	5.00E+05
hPlpM	3	4.79E+05	sStudM	3	5.00E+05	hPlpM	5	4.79E+05
sStudM	3	5.00E+05	sStudM	8	3.69E+05	sStudM	3	4.34E+05
sStudM	5	3.69E+05	sSawM	5	3.71E+05	sStudM	5	5.00E+05
sSawM	3	4.36E+05	BioEnergy	1	4.20E+05	sSawM	5	4.36E+05
BioEnergy	3	4.20E+05	BioEnergy	3	4.20E+05	BioEnergy	5	4.20E+05
BioEnergy	8	1.22E+05	BioEnergy	5	4.20E+05			
			BioEnergy	6	4.20E+05			
			BioEnergy	7	2.41E+05			
			BioEnergy	8	4.20E+05			
SP3			SP4			SP5		
Mill	location	Capacity	mill	location	Capacity	mill	location	Capacity
sPlpM	5	5.00E+05	hPlpM	6	3.71E+05	hPlpM	6	4.79E+05
hPlpM	5	4.79E+05	sStudM	3	5.00E+05	sStudM	1	5.00E+05
sStudM	3	3.69E+05	sStudM	8	4.34E+05	sStudM	8	4.34E+05
sStudM	5	5.00E+05	sSawM	5	4.36E+05	sSawM	3	3.71E+05
sSawM	5	3.71E+05	hSawM	6	5.00E+04	BioEnergy	1	4.20E+05
BioEnergy	5	4.20E+05	BioEnergy	1	4.20E+05	BioEnergy	2	4.20E+05
			BioEnergy	3	4.20E+05	BioEnergy	3	4.20E+05
			BioEnergy	5	4.20E+05	BioEnergy	6	2.41E+05
			BioEnergy	6	4.20E+05	BioEnergy	7	4.20E+05
			BioEnergy	7	2.41E+05	BioEnergy	8	4.20E+05
			BioEnergy	8	4.20E+05			

In Scenario SP2, the price of softwood final products increased by 20% and the price of hardwood final products decreased by the same percentage. Most of the installed capacities are the same as in the basic scenario, and there is a larger stud mill and an extra BioEnergy plant in integrated approach. Although the amount of harvest in the integrated approach is still less than the separate approach, the gap is decreased in comparison with the basic scenario. The net profit of the system in this scenario is more than the basic scenario S0. This is reasonable, as this scenario is consistent with the generated forest, in which softwood is the dominant species.

In scenario SP3, the price of lumber decreased by 20%, and the price of market pulp increased by the same percentage. The capacity of softwood pulpmill decreased in the integrated approach, and there is no other change in the capacities although the locations

of the two softwood stud mills are reversed. The net profit in the system increased in comparison with the basic scenario, S0. This is reasonable, because some of the logs, which are previously processed at sawmills, will go through the pulp mills. The increase in the price of market pulp will result in net profit increase in the system.

In scenario SP4, the price of lumber increased by 20%, and the price of pulp decreased by 20%. In both the separate and integrated approaches, there is no softwood pulp mill in the system, a hardwood sawmill is installed, and the number of BioEnergy plants is increased. The logs and chips which are processed at sPlpM in the basic scenario, are now processed in the BioEnergy plants. As the price of pulp in the system decreased, the total profit in the system is also decreased.

In scenario SP5, the price of BioEnergy increased by 50%. The number of BioEnergy plants and their capacities show that these plants are more profitable in comparison with others. There are six BioEnergy plants in the network and five of them are at their maximum capacity. Softwood pulp log and softwood chip can be processed in both pulp mills and BioEnergy plants. When it is more profitable to generate electricity in comparison with pulp, either because of increase in the price of energy or decrease in the price of pulp, the system prefer to install BioEnergy rather than sPlpM.

## Chapter 5: Conclusion and future research directions

### 5.1. Summary

In this thesis, two decision making approaches for integrated forest network design have been investigated, using mathematical models and laboratory data sets. Although the results of this research are applied only on simulated forests, they provide valuable insights regarding forest management modelling, capacity expansions, and the effect of these decisions on each other.

As explained in the first chapter, there are two decision making approaches for the integrated network design problem, the separate approach and the integrated approach. In the separate approach, which is currently practiced, the forest management is done in a separate phase. The annual harvest is defined in this phase and it becomes a framework for capacity expansion and designing the rest of the network. In the integrated approach, forest management, capacity decisions, and network flow are considered simultaneously.

The second chapter provides a review of the existing literature related to current work. As mentioned in this chapter, there is dearth of research in which economic issues and capacity expansion are considered in forest management modelling. The integrated

mathematical model proposed in this thesis addresses this gap in the literature. On one hand, the proposed model extends the forest management model by considering capacity decisions, and on the other hand, it extends the capacity expansion model by considering forest management decisions.

Chapter 3 provides a more specific description of the problem and the related mathematical models. In the first section of this chapter, the forestry network and its elements are explained in more detail. Mathematical models are proposed for both the separate approach and the integrated approach. In the separate approach, the classical forest management Model I is used in the first phase and the results of the model are used as the wood flow in the network design model. In the integrated model, both forest management and capacity decisions are included in the same model.

In chapter 4, numerical experiments are conducted, and the results are used to give insight into the research questions. In the first section of this chapter, the data used to test the models are introduced. As the first step, a simulation framework is introduced to create forest scenarios for analysis. In this framework it is possible to create different forest scenarios, based on different stand characteristics such as initial age, site class, cover type, and stocking.

In addition to different forest scenarios, different data are also needed for different types of plants in the system, including different capacity options and their related installation cost, fixed and variable operating costs, and their possible locations. Different flows of material exist in the system: flow of logs from forest to different types of mill, flow of intermediate products from one mill to another, and the flow of final products from each mill.

Using the aforementioned data, the model's solutions are discussed. The discussion includes the comparison between the two approaches in terms of the objective functions and different costs in the system, the harvesting pattern, installed capacities, and their locations. The models are tested with six different randomly generated sets of forests. The results are quite similar for different scenarios in which the forests are generated based on the same probability distributions and the rest of the data remain the same. In all problem



sets, the integrated approach has the superior performance in comparison with the separate approach.

Another analysis that was done in this chapter was about the effect of final products price on the network design. Although the integrated approach has better performance in all scenarios, this superiority is more distinguished when the profitable final products in the system are not consistent with the forest products. This superiority highlights the importance of considering the capacity issues in forest management.

It is worthwhile to explain that the integrated approach may have some advantages and disadvantages over the separate approach. Some of these advantages are:

1. Theoretically, to find a solution for a problem, optimizing the whole problem consists in finding a global optimum while optimizing subset problems consists in finding local optima. Generally, a global optimum is better than local optima, especially in complex systems. [In some cases, they have similar results.]
2. Economically, we can select our harvesting areas based on current capacities and choose the best expansion strategies based on available resources and market situations. This will result in a consistent system which helps to earn more money from the forest.
3. Environmentally, not only is it possible to consider environmental constraints in the integrated model, it is also possible to consider economic objectives and select the harvesting areas strategically, economically and consistent with capacity. In other words, while considering environmental issues, changing the forest management's objectives from harvest based ones toward economic objectives, based on the potential capacity results in more logical use of forests.

As this approach has a holistic view on strategic decision making and because of the mentioned advantages, one may initially say that this approach will surely have better results, but further investigation should be done to prove its superiority and effectiveness because:

1. This approach would be a more complex problem, and finding an optimal or near optimal solution may not be an easy task.

2. Implementing this approach in reality may be difficult because many different ideas from different sectors should be considered.
3. In this research, the share for each of the elements has not considered. Having an integrated approach may increase the overall performance of the system, but to make all elements contribute to the system, short and long-term profitability should be guaranteed. This may apply to the model by adding constraints for minimum profitability for each elements.
4. Selecting an overall objective function is not easy. In forest management there are objectives such as maximizing the harvested wood, while in network design problems, most objectives are economic, such as net present value and return on investment. Therefore, deciding about an objective function that satisfies both the forest sector and production sector is important for an effective integrated approach.

As can be seen in all the runs that have been done, the integrated approach gives a consistent advantage over the separate approach. Although in some cases the advantage may appear small, note that we have assumed all stands are equally accessible and that the harvest costs of all stands are the same. If we were to differentiate stand access costs and stand harvest costs, the advantage of the integrated approach would be more obvious.

## 5.2. Future research

### **Proposing efficient algorithms**

The present work has investigated two different approaches using mathematical models. The forest in the data set was a small forest with 3000 stands, and the models were solved using Gurobi. Even with this size of forest the solution time was significant. Increasing the number of stands, products, and mill, would result in a large-scale problem. Finding an optimal or even near optimal solution in a reasonable time would be a challenge.

One of the ways to solve the mathematical models is to use methods that break down the problem into smaller sub-problems. Among these methods is the Fixed and Relax [48] algorithm, which repeatedly solves smaller size problems with a smaller number of binary variables. Solving a forest management problem with a defined MIP gap or within a specific time, and then fixing its variables and passing them to the capacity expansion model as a parameter, will reduce the time of the capacity expansion solution. Solving the capacity expansion problem, with a defined gap and passing the expansion decision variables to forest management, will make the integrated model simpler. Moving back and forth between these sub-problems after the whole model converges to a solution, is an efficient method to find a good answer in a reasonable amount of time.

### **Considering uncertainty in final product price**

Proposing an efficient and robust approach toward forest management and capacity planning in an uncertain environment is another important direction for futures research. In section 4.2.3, different pricing scenarios for the final products were investigated. Different pricing scenarios result in different network designs. Uncertainty about different elements in the supply chain, such as demand and price, will affect the network design, including capacities and harvesting patterns in forests. A robust strategic plan is key to mitigating the risk of these uncertainties. There is limited research that uses stochastic programming to deal with uncertainty in forestry network design and even in those cases their scopes are different from this research. For example, the forest management is not considered as a part of the designing process [36] which should be modified due to future

uncertainties. Stochastic mathematical models [49] can be used to model these networks under uncertainty.

### **Modelling real forest network**

As mentioned before, the models and approaches in this thesis are tested using laboratory data sets. Applying the mathematical models to the case of a real forest is a practical extension of this thesis. Real forests are very large. There are also many existing facilities which should be considered as a part of the network. Proposing a Decision Support System (DSS) to help the manager evaluating their strategies in reality would be a challenge. However, it is not beyond achievement. If we fix the capacity decisions, what remains is a linear program and reasonably solvable. Similarly, if we fix the harvest decisions, what remains is a modest sized integer program. By working iteratively between these two problems, it would appear possible to produce good solutions.

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## Appendix A: Excel file for stand generation

As explained in section 4.2.1, each stand has different characteristics, which are generated based on a defined probability, using Microsoft excel Figure 32 is a snapshot of the Excel spreadsheet file created by Dr. Eldon Gunn. In this spreadsheet, the number of stands, the expected value of the stands area, and the cumulative probability of different characteristics are inputs. Based on this information the stands and their characteristics will be generated using corresponding buttons. For example, Genages generates initial age for each stand based on the defined probability.

Age	Cum Pct	Site	CumPct	Cover	CumPct	Stock	Cum Pct	Region	CumPct
0	5	3	10	Soft	60	30	15	1	6
20	25	4	40	Mixed	80	40	35	2	14
40	45	5	70	Hard	100	50	65	3	20
60	70	6	90			60	85	4	26
80	90	7	100			70	95	5	31
100	95	8	100			80	100	6	38
120	100							7	45
200	100							8	52
								9	59
								10	65
								11	72
								12	79
								13	85
								14	92
								15	100

Figure 32: Excel file for stand characteristic generation

The Visual Basic macros that allow the simulation are given below:

```

Global AgeDistAges(8), AgeDistCum(8)
Sub ReadADist()
For i = 1 To 8
    AgeDistAges(i) = Range("AgeDist").Offset(i, 0)
    AgeDistCum(i) = Range("AgeDist").Offset(i, 1)
Next i
End Sub

Sub GenAges()
Dim Genage As Variant
Call ReadADist
k = 1
standno = Range("Stand").Offset(k, 0)
While standno > 0
    r1 = 100 * Rnd()
    For i = 1 To 8
        If r1 < AgeDistCum(i) Then
            If (i = 1) Then
                Genage = 0
            Else
                pct = (r1 - AgeDistCum(i - 1)) / (AgeDistCum(i) - AgeDistCum(i - 1))
                Genage = AgeDistAges(i - 1) + pct * (AgeDistAges(i) - AgeDistAges(i -
1))
            End If
            r1 = 200
        End If
    Next i
    Genage = Int(Genage / 5 + 0.499999) * 5
    Range("Stand").Offset(k, 2).Value = Genage
    k = k + 1
    standno = Range("Stand").Offset(k, 0)
Wend

End Sub

Sub genarea()

Dim Genage As Variant
MeanArea = Range("MArea").Value

k = 1
standno = Range("Stand").Offset(k, 0)
While standno > 0
    r1 = Rnd()
    Area = -MeanArea * Log(r1)

    Range("Stand").Offset(k, 1).Value = Area
    k = k + 1
    standno = Range("Stand").Offset(k, 0)
Wend
End Sub

Sub gensite()
Dim SiteClass(6), SiteDistCum(6)

For i = 1 To 6
    SiteClass(i) = Range("Site").Offset(i, 0)

```

```

        SiteDistCum(i) = Range("Site").Offset(i, 1)
        Debug.Print SiteClass(i), SiteDistCum(i)
    Next i

k = 1
standno = Range("Stand").Offset(k, 0)
While standno > 0
    r1 = 100 * Rnd()
    For i = 1 To 6
        If r1 < SiteDistCum(i) Then
            Site = SiteClass(i)
            Exit For
        End If
    Next i

    Range("Stand").Offset(k, 3).Value = Site
    k = k + 1
    standno = Range("Stand").Offset(k, 0)
Wend
End Sub

Sub genregion()
    Dim RegClass(27), RegDistCum(27)

    For i = 1 To 27
        RegClass(i) = Range("RegTyp").Offset(i, 0)
        RegDistCum(i) = Range("RegTyp").Offset(i, 1)
        Debug.Print RegClass(i), RegDistCum(i)
    Next i

    k = 1
    standno = Range("Stand").Offset(k, 0)
    While standno > 0
        r1 = 100 * Rnd()
        For i = 1 To 27
            If r1 < RegDistCum(i) Then
                Site = RegClass(i)
                Exit For
            End If
        Next i

        Range("Stand").Offset(k, 6).Value = Site
        k = k + 1
        standno = Range("Stand").Offset(k, 0)
    Wend
End Sub

Sub gencover()
    Dim CoverClass(6), CoverDistCum(6)
    Dim Cov(30000)
    numstand = Range("NumStands").Value
    For i = 1 To 3
        CoverClass(i) = i
        CoverDistCum(i) = Range("Cover").Offset(i, 1)
    Next i
    k = 1
    standno = k

```

```

While standno <= numstand
    r1 = 100 * Rnd()
    For i = 1 To 3
        If r1 < CoverDistCum(i) Then
            cover = CoverClass(i)
            Exit For
        End If
    Next i

    Cov(k) = cover
    k = k + 1
    standno = k
Wend

For k = 1 To numstand
    Range("Stand").Offset(k, 4).Value = Cov(k)
Next k

End Sub

Sub genstock()
    Dim StockPct(6), StockDistCum(6)
    Dim Stock(30000)
    numstand = Range("NumStands").Value
    For i = 1 To 6
        StockPct(i) = Range("Stock").Offset(i, 0)
        StockDistCum(i) = Range("Stock").Offset(i, 1)
        Debug.Print StockPct(i), StockDistCum(i)
    Next i

    k = 1
    standno = k
    While standno <= numstand
        r1 = 100 * Rnd()
        For i = 1 To 6
            If r1 <= StockDistCum(i) Then
                stocking = StockPct(i)
                Exit For
            End If
        Next i

        Stock(k) = stocking
        k = k + 1
        standno = k
    Wend

    For k = 1 To numstand
        Range("Stand").Offset(k, 5).Value = Stock(k)
    Next k
End Sub

Sub WriteStnds()
    numstand = Range("NumStands").Value
    Open "StandData" For Output As #1

```

```
Print #1, numstand
For k = 1 To numstand
standno = Range("Stand").Offset(k, 0).Value
Area = Range("Stand").Offset(k, 1).Value
Age = Range("Stand").Offset(k, 2).Value
Site = Range("Stand").Offset(k, 3).Value
cover = Range("Stand").Offset(k, 4).Value
Stock = Range("Stand").Offset(k, 5).Value / 100
Region = Range("Stand").Offset(k, 6).Value
Print #1, standno; Area; Age; Site; cover; Stock; Region
Next k
Close #1
End Sub
```

## Appendix B: C++ and Gurobi procedures and codes

In this Appendix, the procedure that is used to solve the models is explained briefly. The codes are written in C++ and the mathematical models are solved using Gurobi. The main steps in the C++ codes with some examples are presented as follows.

### 1. Reading data from text files

In this step, different data and parameters of the models are read from different text files and saved in different variables. For example, the next piece of code shows how different parameters for each stand are read and saved in variables.

```
    sprintf_s(Stands_data, "c:\\Users\\User\\Dropbox\\Thesis\\Mathematical
Model\\Data\\Input\\Stands.txt");
    string Result = Model_Output;
    string XIJResult = Model_XIJ;
    ifstream Stand_stream(Stands_data, ios::in);
    if (!Stand_stream)
    {
        cout << "can't open data file1";
        getchar();
        exit(0);
    }

    struct stand_struct
    {
        int stand_id;
        float stand_Area;
        int stand_Age;
        int stand_Site;
        int stand_Cover;
        float stand_Stock;
        int stand_TSheds;
    };

    stand_struct Stand[nStands];

    Stand_stream >> text;
    Stand_stream >> text;
    Stand_stream >> text;
    Stand_stream >> text;
    Stand_stream >> text;
    Stand_stream >> text;
    Stand_stream >> text;
    Stand_stream >> text;
    Stand_stream >> text;

    for (int i = 0; i < nStands; i++) {
        Stand_stream >> Stand[i].stand_id;
        Stand_stream >> Stand[i].stand_Area;
```

```

Stand_stream >> Stand[i].stand_Age;
Stand_stream >> Stand[i].stand_Site;
Stand_stream >> Stand[i].stand_Cover;
Stand_stream >> Stand[i].stand_Stock;
Stand_stream >> Stand[i].stand_TSheds;
}
cout << "Stand characteristic is read" << endl;
Stand_stream.close();

```

## 2. Defining the decision variables in the model and pass them to Gurobi

To make a decision variable in Gurobi C++ interface the statement “model.addVar (lower bound, Upper bound, Objective function multiplier, Type, Name)” should be used [47]. The next piece of code shows how the decision variable RegionLogtomillPeriod is made. This decision variable is defined as a 5-dimensional Gurobi variable vector.

```

GRBVarVector5 RegionLogtomillPeriod;
GRBVarVector4 RegionLogtomillPeriod4;
GRBVarVector3 RegionLogtomillPeriod3;
GRBVarVector2 RegionLogtomillPeriod2;
GRBVarVector RegionLogtomillPeriod1;

string RegionLogtomillPeriod_Name;
for (int t = 0; t < nPeriods; t++)
{
    for (int l = 0; l < nLogType; l++)
    {
        for (int r = 0; r < nRegion; r++)
        {
            for (int m = 0; m < nCapacity; m++)
            {
                for (int lo = 0; lo < nLocation; lo++)
                {
                    RegionLogtomillPeriod_Name =
"RegionLogtomillPeriod(" + itos(t + 1) + "," + itos(l + 1) + "," + itos(r + 1) +
"," + itos(m + 1) + "," + itos(lo + 1) + ")";

                    RegionLogtomillPeriod1.push_back(model.addVar(0, 0, 0, GRB_CONTINUOUS,
RegionLogtomillPeriod_Name));

                    RegionLogtomillPeriod_Name.clear();
                }

                RegionLogtomillPeriod2.push_back(RegionLogtomillPeriod1);
                RegionLogtomillPeriod1.clear();
            }

            RegionLogtomillPeriod3.push_back(RegionLogtomillPeriod2);
            RegionLogtomillPeriod2.clear();
        }
    }
}

```

```

RegionLogtomillPeriod4.push_back(RegionLogtomillPeriod3);
        RegionLogtomillPeriod3.clear();
    }
    RegionLogtomillPeriod.push_back(RegionLogtomillPeriod4);
    RegionLogtomillPeriod4.clear();
}
model.update();

for (int t = 0; t < nPeriods; t++)
    for (int r = 0; r < nRegion; r++)
        for (int lo = 0; lo < nLocation; lo++)
            for (int lm = 0; lm <
LogMillPriceInt_Vec2.size(); lm++)
                {

                    RegionLogtomillPeriod[t][LogMillPriceInt_Vec2[lm][0]][r][LogMillPriceInt_Ve
c2[lm][1]][lo].set(GRB_DoubleAttr_UB, GRB_INFINITY);
                }

    cout << " RegionLogtomillPeriod var is made" << endl;

```

### 3. Defining the constraints of the model and pass them to Gurobi

To make a constraint in Gurobi using C++ interface the statement “model.addConstr(constraint left hand side, Constraint type, constraint right hand side, constraint name” should be used [47]. The next piece of code shows how the constraint PlantFlowInConstraint is made. In this constraint, the operating level of a plant is defined based on its input. This decision variable define as a 3 dimensional Gurobi constraint array.

```

GRBLinExpr ***PlantFlowInConstraint_LHS = new GRBLinExpr **[nPeriods];
    for (int t = 0; t < nPeriods; t++)
    {
        PlantFlowInConstraint_LHS[t] = new GRBLinExpr *[nCapacity];
        for (int n = 0; n < nCapacity; n++)
            PlantFlowInConstraint_LHS[t][n] = new
GRBLinExpr[nLocation];
    }

    for (int t = 0; t < nPeriods; t++)
        for (int m = 0; m < nCapacity; m++)
            for (int l = 0; l < nLocation; l++)
            {
                for (int lg = 0; lg < nLogType; lg++)
                    for (int r = 0; r < nRegion; r++)

```



```

PlantFlowInConstraint_LHS[t][m][1] =
PlantFlowInConstraint_LHS[t][m][1] + RegionLogtomillPeriod[t][lg][r][m][1] *
LogMillPercent_Vec[m][lg];

for (int p = 0; p < nIntType; p++)
    for (int m1 = 0; m1 < nCapacity; m1++)
        for (int l1 = 0; l1 < nLocation; l1++)
            {
                for (int i = 0; i < IntMillPriceInt_Vec2.size(); i++)
                    if (IntMillPriceInt_Vec2[i][0] == p &&
IntMillPriceInt_Vec2[i][1] == m1 && IntMillPriceInt_Vec2[i][2] == m)
                        PlantFlowInConstraint_LHS[t][m][1] =
PlantFlowInConstraint_LHS[t][m][1] + IntMilltoMillPeriod[t][p][m1][l1][m][1] *
IntMillPriceInt_Vec2[i][5];
            }
        }

GRBLinExpr ***PlantFlowInConstraint_RHS = new GRBLinExpr
**[nPeriods];
for (int t = 0; t < nPeriods; t++)
{
    PlantFlowInConstraint_RHS[t] = new GRBLinExpr *[nCapacity];
    for (int m = 0; m < nCapacity; m++)
        PlantFlowInConstraint_RHS[t][m] = new
GRBLinExpr[nLocation];
}

for (int t = 0; t < nPeriods; t++)
    for (int m = 0; m < nCapacity; m++)
        for (int l = 0; l < nLocation; l++)
            {
                PlantFlowInConstraint_RHS[t][m][l] = OperatingLevel[t][m][l];
            }

GRBConstr ***PlantFlowInConstraint = new GRBConstr **[nPeriods];
for (int t = 0; t < nPeriods; t++)
{
    PlantFlowInConstraint[t] = new GRBConstr *[nCapacity];
    for (int m = 0; m < nCapacity; m++)
        PlantFlowInConstraint[t][m] = new GRBConstr[nLocation];
}

string PlantFlowInConstraint_Name;

for (int t = 0; t < nPeriods; t++)
    for (int m = 0; m < nCapacity; m++)
        for (int l = 0; l < nLocation; l++)
            {
                PlantFlowInConstraint_Name = "PlantFlowInConstraint(" + itos(t
+ 1) + "," + itos(m + 1) + "," + itos(l + 1) + ")";

                PlantFlowInConstraint[t][m][l] =
model.addConstr(PlantFlowInConstraint_LHS[t][m][l], GRB_EQUAL,
PlantFlowInConstraint_RHS[t][m][l], PlantFlowInConstraint_Name);
                PlantFlowInConstraint_Name.clear();
            }
}

```

```
delete PlantFlowInConstraint_LHS;
delete PlantFlowInConstraint_RHS;
cout << "Flow in constraint is made ";
```

#### 4. Solving the models using Gurobi solver.

The statement in this step is “model.optimize”. The next piece of code shows how the model is solved for the separate and the integrated approaches. Through this piece, the optimization is done three times. The first time is for the first phase of the separate approach, the second time is for the second phase of the separate approach, and the third time is for the integrated approach. In the first phase of the separate approach, all the objective function multipliers except wood volume multipliers are equal to zero. The Alpha multiplier is equal to 2000. After optimizing this model the  $X_{ik}$  decision variables are fixed, and the multipliers of the objective function are updated. In this phase, the wood volume multiplier is equal to 0, the final revenue multiplier is equal -1, and the costs multipliers are equal to 1. The result of this model is the solution for the separate approach. The integrated approach is the same as the second phase of the separate approach, but the  $X_{ik}$  decision variables are not fixed.

#### // Separate approach

```
VolMult = -1;
RevFinalMult = 0;
TransMult = 0;
TransLogMult = 0;
TransIntMult = 0;
HarvMult = 0;
LandOwnerMult = 0;
OperateFixMult = 0;
OperateVarMult = 0;
CapMult = 0;

for (int t = 0; t < nPlanningHorizon; t++)
{
    TotVolPer[t].set(GRB_DoubleAttr_Obj, VolMult);
}
```

```

        for (int t = 0; t < nPeriods; t++)
        {
            RevFinalMult); TotFinalRevPer[t].set(GRB_DoubleAttr_Obj, dFact[t] *
TransLogMult); TotTransLogPer[t].set(GRB_DoubleAttr_Obj, dFact[t] *
TransIntMult); TotTransIntPer[t].set(GRB_DoubleAttr_Obj, dFact[t] *
LandOwnerMult); TotHarvCstPer[t].set(GRB_DoubleAttr_Obj, dFact[t] * HarvMult);
OperateFixMult); TotalLandOwnerCostPer[t].set(GRB_DoubleAttr_Obj, dFact[t] *
OperateVarMult); TotFixOperatingCostPer[t].set(GRB_DoubleAttr_Obj, dFact[t] *
TotVarOperatingCostPer[t].set(GRB_DoubleAttr_Obj, dFact[t] *
ObjectiveFunctionPer[t].set(GRB_DoubleAttr_Obj, 0);

        }
        TotCapCost.set(GRB_DoubleAttr_Obj, CapMult);
        TotAlpha.set(GRB_DoubleAttr_Obj, AlphaMult);
        model.update();
        model.optimize();

        VolMult = 0;
        RevFinalMult = -1;
        TransMult = 1;
        TransLogMult = 1;
        TransIntMult = 1;
        HarvMult = 1;
        LandOwnerMult = 1;
        OperateFixMult = 1;
        OperateVarMult = 1;
        CapMult = 1;
        AlphaMult = 2000;

        for (int t = 0; t < nPlanningHorizon; t++)
        {
            TotVolPer[t].set(GRB_DoubleAttr_Obj, VolMult);
        }

        for (int t = 0; t < nPeriods; t++)
        {
            RevFinalMult); TotFinalRevPer[t].set(GRB_DoubleAttr_Obj, dFact[t] *
TransLogMult); TotTransLogPer[t].set(GRB_DoubleAttr_Obj, dFact[t] *
TransIntMult); TotTransIntPer[t].set(GRB_DoubleAttr_Obj, dFact[t] *
LandOwnerMult); TotHarvCstPer[t].set(GRB_DoubleAttr_Obj, dFact[t] * HarvMult);
OperateFixMult); TotalLandOwnerCostPer[t].set(GRB_DoubleAttr_Obj, dFact[t] *
TotFixOperatingCostPer[t].set(GRB_DoubleAttr_Obj, dFact[t] *

```

```

OperateVarMult);      TotVarOperatingCostPer[t].set(GRB_DoubleAttr_Obj, dFact[t] *
                      ObjectiveFunctionPer[t].set(GRB_DoubleAttr_Obj, 0);

                      }
                      TotCapCost.set(GRB_DoubleAttr_Obj, CapMult);
                      TotAlpha.set(GRB_DoubleAttr_Obj, AlphaMult);

                      for (int i = 1; i <= nStands; i++)
                      {
                          for (int k = 1; k <= nPrescriptions; k++)
                          {
                              if (XIK[i - 1][k - 1].get(GRB_DoubleAttr_X) > 0)
                              {
                                  XIK[i - 1][k - 1].set(GRB_DoubleAttr_UB, XIK[i -
1][k - 1].get(GRB_DoubleAttr_X) + 0.00005);
                                  XIK[i - 1][k - 1].set(GRB_DoubleAttr_LB, XIK[i -
1][k - 1].get(GRB_DoubleAttr_X) - 0.00005);
                              }
                              else
                                  XIK[i - 1][k - 1].set(GRB_DoubleAttr_UB, 0);
                          }
                      }

                      model.getEnv().set(GRB_DoubleParam_MIPGap, 0.01);
                      model.update();
                      model.optimize();

// Integrated approach

                      for (int i = 0; i < IK_Vec2.size(); i++)
                      {
                          i1 = IK_Vec2[i][0];
                          k1 = IK_Vec2[i][1];
                          XIK[i1 - 1][k1 - 1].set(GRB_DoubleAttr_UB, GRB_INFINITY);
                          XIK[i1 - 1][k1 - 1].set(GRB_DoubleAttr_LB, 0);
                      }

                      TotAlpha.set(GRB_DoubleAttr_Obj, AlphaMult);
                      model.getEnv().set(GRB_DoubleParam_MIPGap, 0.01);
                      model.update();
                      model.optimize();

                      }

```

5. Writing the solution and save them as excel file. To get a variable name and value statements “variable.get(GRB\_StringAttr\_VarName)” and “variable.get(GRB\_DoubleAttr\_X)” are used, respectively. The next piece of code

shows how the model result for RegionPeriodHarvest and RegionLogtomillPeriod variables are written and saved in the file.

```

ofstream jr3(Result1, ios::app);
ofstream jr4(XIJResult, ios::app);
if (model.get(GRB_IntAttr_Status) == GRB_OPTIMAL)
{
    jr3 << "RegionPeriodHarvest " << endl;
    jr3 << "t" << "," << "w" << "," << "r" << endl;
    jr3 << "n" << " , " << "r" << " , ";
    for (int t = 0; t < nPlanningHorizon; t++)
        jr3 << t + 1 << " , ";
    for (int n = 0; n < nWoodType; n++)
        for (int r = 0; r < nRegion; r++)
        {
            jr3 << endl;
            jr3 << n + 1 << " , " << r + 1;
            for (int t = 0; t < nPlanningHorizon; t++)
            {
                jr3 << " , " <<
RegionPeriodHarvest[t][n][r].get(GRB_DoubleAttr_X);
            }
        }
    jr3 << endl;
    jr3 << "RegionLogtomillPeriod" << endl;
    jr3 << "t" << " , " << "l" << " , " << "r" << " , " << "lo" << " , " <<
"m" << endl;
    for (int t = 0; t < nPeriods; t++)
        for (int l = 0; l < nLogType; l++)
            for (int r = 0; r < nRegion; r++)
                for (int lo = 0; lo < nLocation; lo++)
                    for (int m = 0; m < nCapacity; m++)
                    {
                        if
(RegionLogtomillPeriod[t][l][r][m][lo].get(GRB_DoubleAttr_X) > 0.0001)
                        {
                            jr3 << t << " , " << l << " , " << r << " , " << lo << " , " <<
m << " , " << RegionLogtomillPeriod[t][l][r][m][lo].get(GRB_DoubleAttr_X) << endl;
                        }
                    }
}
}

```